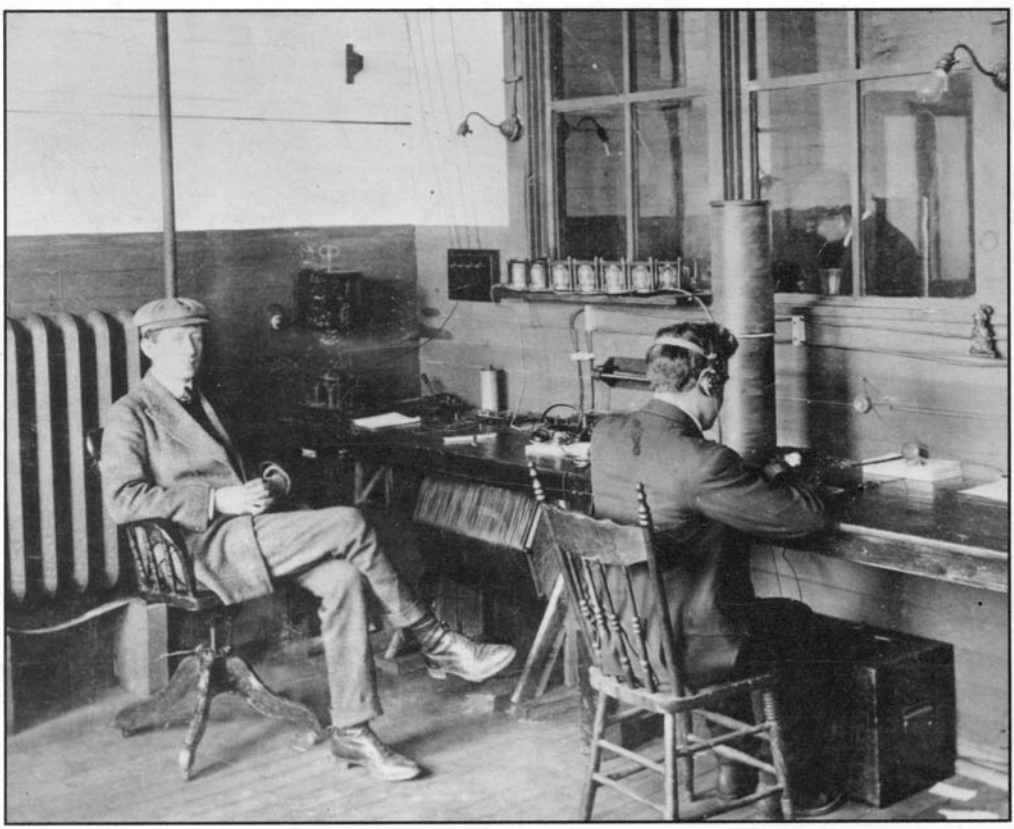
AWA

THE AWA REVIEW



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THE A.W.A. REVIEW

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THE COVER

Receiving room at the Glace Bay, Nova Scotia wireless station. Guglielmo Marconi is sitting to the left while James Holmes is tuning the receiver. This photo was taken October 17, 1907. Note the row of the seven "Gallows Mount" Fleming valves on the window sill. 1907 was early for the application of these valves as a substitute detector.

Photo courtesy of Public Archives of Nova Scotia

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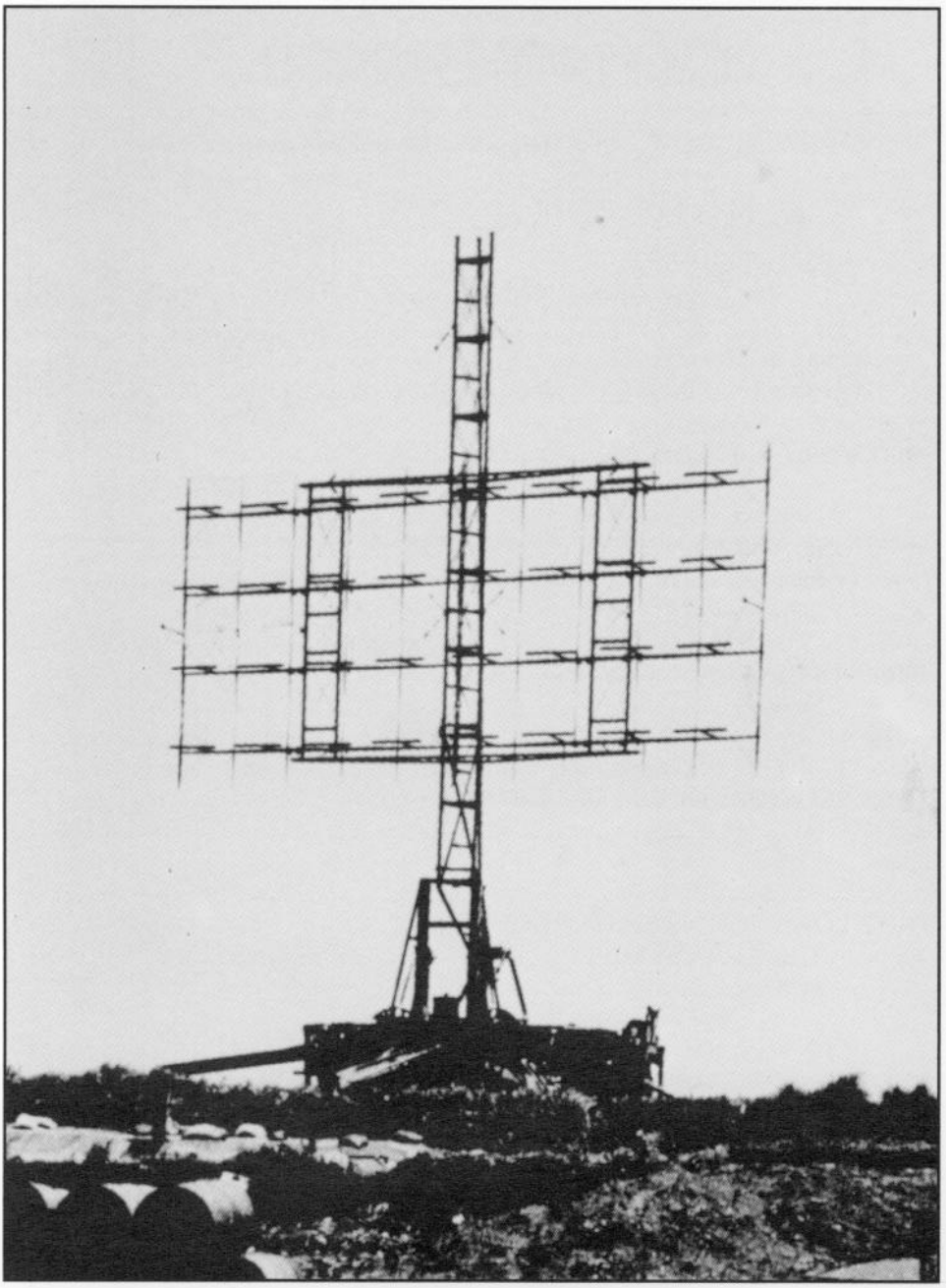

U.S. Army SCR 270 radar, developed in the 1937-40 period. An installation such a this one was in place and operating correctly when it detected the approach of th Japanese air strike force on the morning of December 7, 1941, on its way to bom Pearl Harbor. The SCR 271 was similar, but intended for fixed installation. Se "The International Contest for RADAR," by Ed Lyon, in this volume.

Photo from Reference 1, Bibliography

FOREWORD

Beginning with Volume 1 of *THE AWA REVIEW* in 1986, the Antique Wireless Association has sought for and published the efforts of dedicated workers who have researched and documented the records of past events associated with the history of wireless communications. Ten years later, Volume 9 continues this established tradition by presenting for your approval five papers by experts on their respective subjects.

The life of Gugliemo Marconi, although well documented in the past, is presented in a totally new format by Jim and Felicia Kreuzer, who have coupled the story of this remarkable man with over 120 photos...many never before published...of Marconi, his early equipment, and the products of his various wireless corporations. On this 100-year anniversary of the birth of practical wireless communication, this article is a must for collectors and dealers in Marconi artifacts as well as historians.

Ed Lyon, who has spent the greater part of his professional career working with radar, has authored "The International Contest for RADAR," an authoritative as well as highly entertaining story of the development of the technology, set against the world-wide background of World War II and the race of the English for their national survival. For WW II buffs as well as wireless historians, this extensive and well-illustrated paper is excellent reading.

Ed has also written for us "The Real Story of the Magnetron," the vacuum tube which enabled the development by the Allies of superior radar during World War II. A companion of the RADAR story, it describes the efforts of the international scientific community to develop this key item during a time of great crisis.

Pat Dowd covers the work of Fritz Lowenstein, the forgotten man who originated the use of negative grid bias. In this paper he describes a world of patent attorneys and court cases, and Lowenstein's attempts to claim a legal patent on what he felt was rightfully his.

Author Neil Friedman presents a comprehensive overview of the 83 years of government licensing of US radio amateurs. This article is well illustrated with reproductions of the many versions of licenses issued over the years, and is an excellent guide for collectors of this type of ephemera.

Working under the pressures of an early deadline has imposed the need for some assistance. Special thanks are due to Mrs. Brenda Wilkins of East Stroudsburg, PA who rendered the assorted offerings of the writers and the editor into a common computer format. And a substantial debt of gratitude is offered to Theodore Keller, Professor Emeritus of English of East Stroudsburg University, who gave me the benefit of his detailed review of and many valuable suggestions for the Marconi paper. And, of course, without the actual writers, this book would not exist, and to them the AWA extends its thanks for their many hours of devoted effort.

The Editor

Guglielmo Marconi in 1903. This photo was reproduced from a rare stereocard. Source: Kreuzer collection.

MARCONI - THE MAN AND HIS APPARATUS

By
James H. Kreuzer and Felicia A. Kreuzer
Elma, NY

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INTRODUCTION

As one explores the birth of any great invention, it is often seen that many minds may have come close to the actual discovery but are never recognized by history as major contributors. Thus, the credit for the origin of wireless telegraphy, though sometimes disputed, in our eyes is without serious contention. Guglielmo Marconi had a vision unequaled by any other man, and most importantly, the exceptional fortitude to follow it through. He amazed the world, succeeding finally in his struggle to send wireless messages over long distances. This is his story.

Together let us explore the early influences on Marconi's life. We will follow the experiments which foreshadowed the use of wireless telegraphy in commercial applications, and present some little known facts pertinent to the development of the early equipment. We will also review a history and description of the three main factories where most of his apparatus was produced, complementing it with a photographic review of Marconi wireless gear. These pictures include those that are well known, but also many which are previously unpublished.

THE DAWN OF WIRELESS

On April 25, 1874, an event occurred which would change the world forever: on that day Guglielmo Marconi was born in Bologna, Italy. His first influences proved unusual. His father, Giuseppe, was an able, dignified Catholic Italian businessman. His mother, Annie Jamison, a blue-eyed Protestant Irish girl of Daphne Castle, County Wexford, was descended from a family of well-known whiskey distillers in Dublin. Their first child, Alfonso, had been born nine years before Guglielmo. Neat, tidy, studious and obedient, he was nearly the opposite of his brother.

Guglielmo's boyhood was passed in the country at his father's handsome Villa Grifone estate at Pontecchio, some eleven miles outside the city

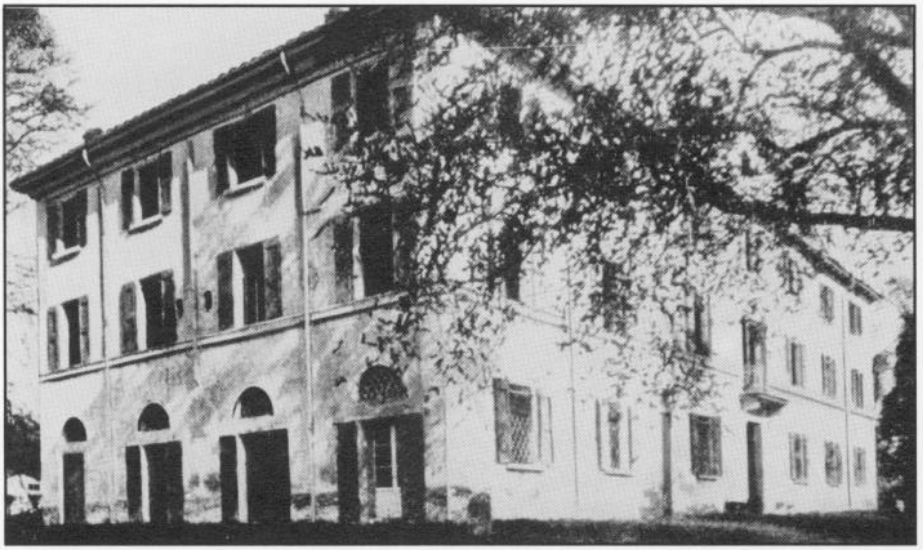


Figure 1. The Villa Grifone where Guglielmo Marconi spent much of his childhood. Source: *Marconi-Master of Space,* Jacot & Collier, 1935

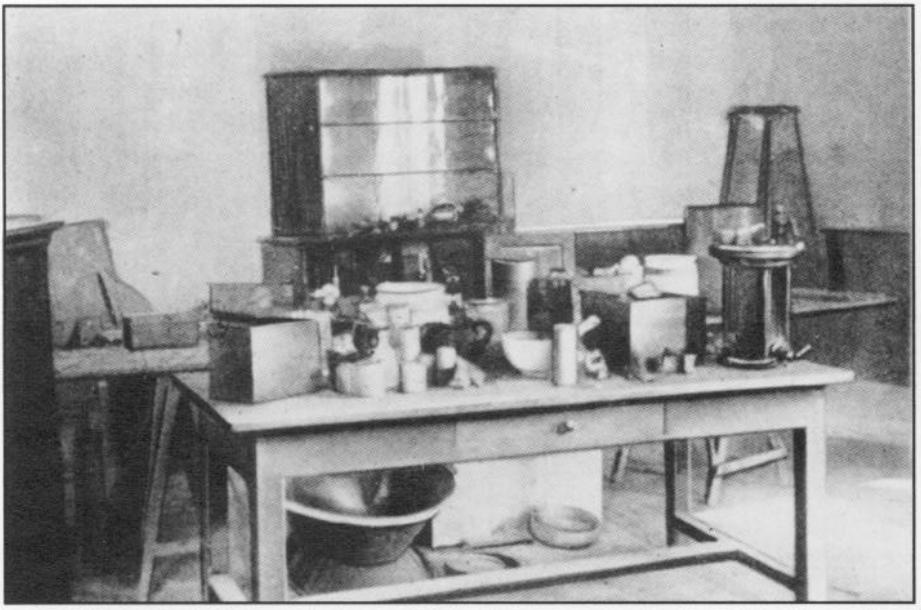


Figure 2. The first wireless laboratory in the world, situated on the third floor of the Villa Grifone. Marconi performed his initial experiments here. Source: Marconi Company Archives

of Bologna. Guglielmo wasn't a particularly clever boy; in fact, he was a bit mischievous. He never lacked imagination, and it was his ability to focus with intense concentration which set him aside from the boys in town. He was always a favorite with his mother; his hobbies became fishing, sailing and horse-back riding, as well as traveling, an asset for the future.

While at home he preferred to spend most of his time in the family library, which concentrated on history, science and technology. In his early years Guglielmo never attended a public school, and although he was tutored in many subjects, he was largely self-taught. His mother also encouraged him to speak and write fluently in English, a decided advantage in later years.

When he was twelve years old he attended the Cavallero Institute in Florence, where he studied physics and chemistry,[1] and quickly ran into difficulties because of his poor Italian vocabulary. On a more positive note, he developed a friendship with a schoolmate, Luigi Solari. At the time he had no way of knowing that Solari would assist him in many of his early experiments, and eventually become an invaluable associate in the field of commercial wireless telegraphy.

At Leghorn the following summer Guglielmo made the acquaintance of a kindly old telegraphist, Nello Marchetti, who took a liking to Marconi and taught him the Morse code.[2] Over the winter, Guglielmo enrolled in the Technical Institute at Leghorn, where he was finally able to secure good grades and enjoy his studies. He was given an introduction to electro-physics by a Professor Rosa and rapidly developed an appetite for an increased knowledge of electricity and its associated areas.[3]

Marconi thoroughly enjoyed playing with electricity, performing "scientific" experiments whenever he could borrow the money from his critical father, who frowned upon his interests. One of his favorite experiments was to bring a wire down from a lightning arrestor on top of the house and hook it to a doorbell. When a sufficient static charge had built up during a thunderstorm, the bell would ring.

Upon noting her son's strong interest in electricity, Annie prevailed upon a neighbor to allow Guglielmo to attend some lectures at the University of Bologna. The neighbor and lecturer was Professor Augusto Righi, a noted physicist at the University. He allowed Marconi to borrow books from the university library, and even perform some experiments. While the professor believed there was nothing new and exciting in the work, he encouraged Marconi to continue.

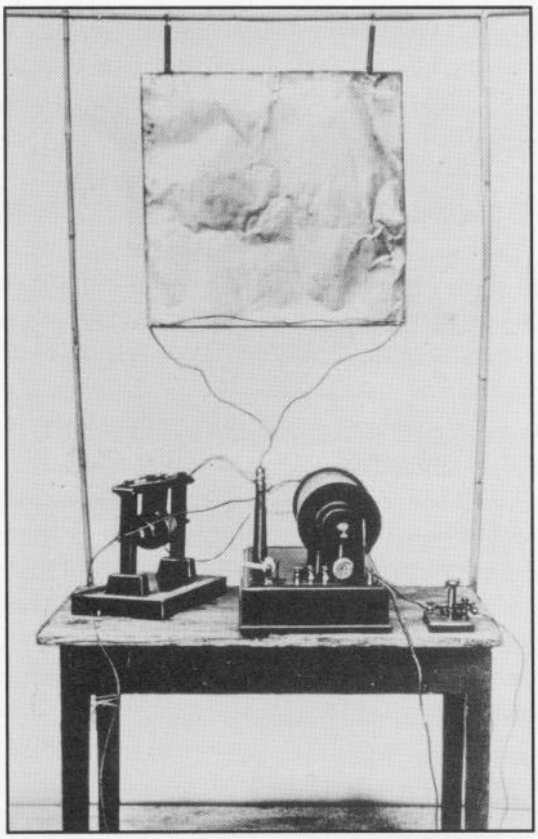


Figure 3. A replica of the first transmitter used at Villa Grifone.
Source: Marconi Company Archives

In the summer of 1894, his twentieth year, Marconi and his brother went to Biellese in the Italian Alps for a vacation. During this time Guglielmo received his inspiration for the idea of using Hertzian waves as a medium by which to communicate. Accounts vary, but several biographies mention that while vacationing Marconi read an obituary on Hertz, and that after reading this the idea of wireless telegraphy was born.[4] Several sources state that the obituary was in an Italian journal, but, unfortunately, no specific reference was ever cited.

However, the mystery of exactly what Marconi read which inspired his life's work appears to have now been solved. In the January, 1894, issue of the Italian electrical journal *Il Nuovo Cimento* two significant articles were printed back-to-back.[5] The first was a seven-page obituary of Hertz written by Antonio Garbasso. This was followed by a six-page article by Augusto Righi detailing

Hertz's electric wave experiments. Piecing together the various clues presented in numerous Marconi biographies indicates that it was probably this issue of *Il Nuovo Cimento* which Marconi read in the summer of 1894.

After finishing the articles by Garbasso and Righi, a revolutionary idea.....

It sparked an interest which was to occupy him day and night, so that during the remainder of his vacation he became preoccupied with sketching and designing diagrams and circuits. On his return to Villa Grifone in Pontecchio he was ready to begin a new group of experiments.

Marconi found it difficult to believe that no other scientist had grasped the commercial possibilities of wireless telegraphy, even though the foundations of the technology were present. Determined to see if his ideas had substance, he set up a primitive laboratory in two rooms on the third floor and began crude experiments with wireless, assisted by his brother, Alfonso.

All of his apparatus at the time was hand-made. This was not only through a lack of funds (he disliked having to plead with his father for lira,) but because the type of apparatus he needed hadn't yet been developed.

In many of his early experiments Marconi was complimented by his young friends and assistants on his uncanny ability to produce serviceable instruments and devices from the most primitive materials. Probably this was due to his vivid imagination, which usually enabled him to foresee the end result of a certain piece of apparatus. This ability was to serve him well throughout his career.

Inspired by Hertz, he repeated the electromagnetic wave experiments, using the adjustable spark gap as the receiver and the parabolic reflectors (Fig. 10), which directed his waves, as an antenna system. The transmitter consisted of an induction coil connected to a spark gap, designed by Professor Righi. It combined four brass balls, immersed in Vaseline and separated by small gaps. He controlled the discharge of the spark gap by means of a telegraph key placed in the primary circuit.

Guglielmo continued to consult with Prof. Righi, who had performed many experiments with Hertzian waves, but still had grave doubts that a system of wireless signaling would ever come to any worthwhile use.[6]

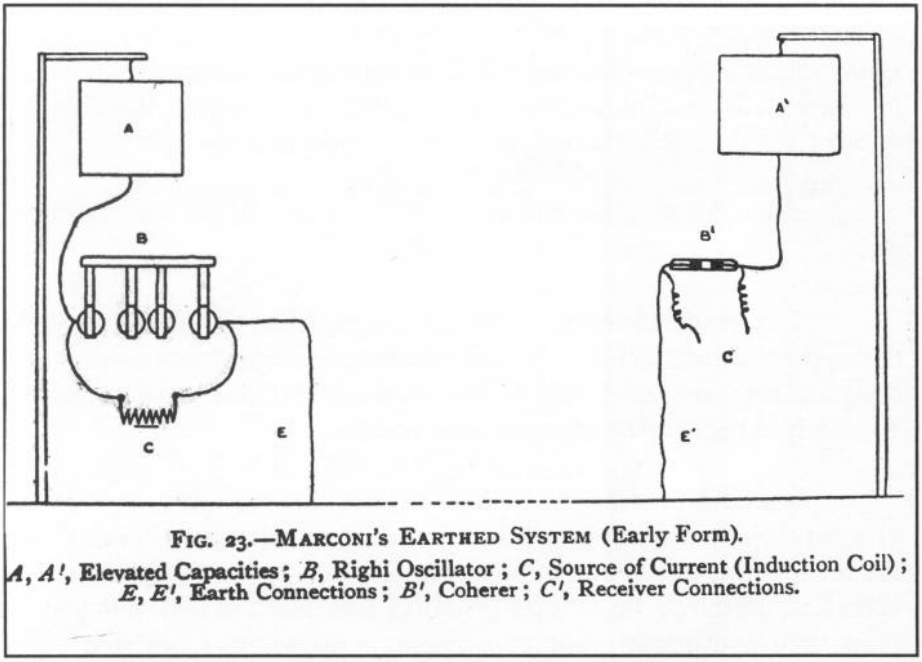


FIG. 23.—MARCONI'S EARTHED SYSTEM (Early Form).
A, *A'*, Elevated Capacities; *B*, Righi Oscillator; *C*, Source of Current (Induction Coil); *E*, *E'*, Earth Connections; *B'*, Coherer; *C'*, Receiver Connections.

Figure 4. Marconi wireless apparatus using a grounded vertical antenna. Source: *Handbook of Wireless Telegraphy*, James Erskine-Murray, 1907

Towards the end of 1894 Guglielmo substituted a device known as the Branley coherer, replacing the Hertz gap as the detector. It consisted of a small glass tube with metal plugs at each end. The middle space was filled with fine metal particles which cohered, or bonded together when in the presence of electromagnetic waves. This device, when connected to a battery and a doorbell, acted as a switch in the circuit, ringing a doorbell in response to a signal. The battery circuit could also be used to operate a tapper, which, when placed close to the coherer, would strike the side of the glass and loosen up the metal granules to be ready for the next signal. (Also see Fig. 25.)

In later developments, he employed a polarized relay to activate the tapper mechanism, simultaneously operating a telegraph printing instrument (Morse inker) to record the signals received. (Also see Fig. 26.) An additional improvement in distance was obtained by connecting metal plates to the spark gap terminals of the transmitter and receiver, in the hope that the longer waves would also provide longer signaling distances.

In December, 1894, after spending countless hours constructing apparatus with no success, he was able to perform a demonstration for his

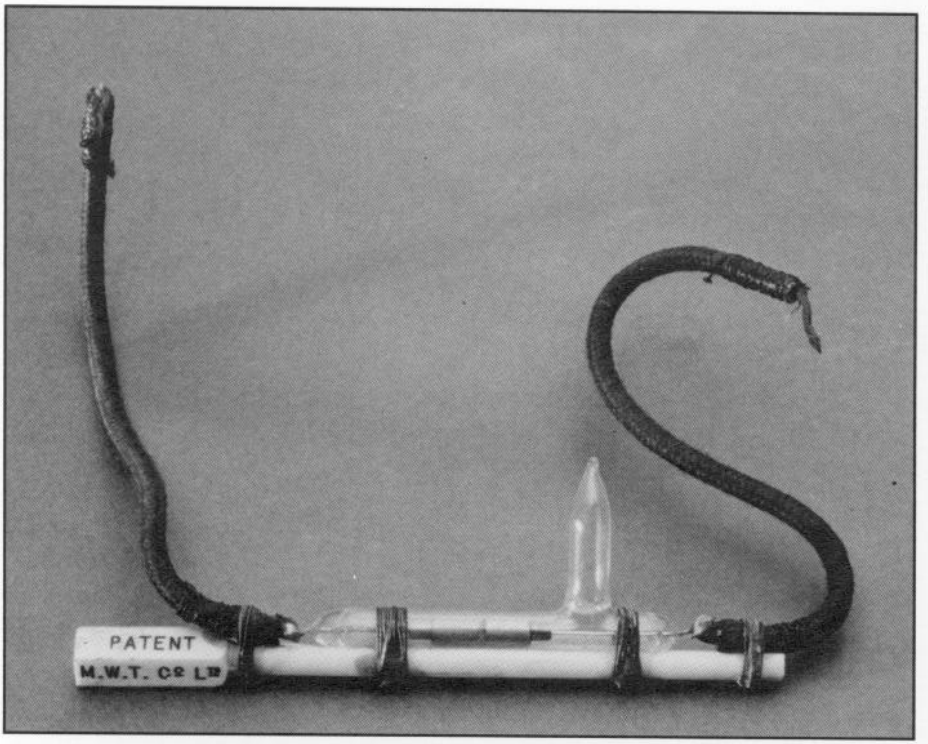


Figure 5. The Marconi Coherer and its ivory supporting rod, which Guglielmo utilized as the heart of his wireless receiver. Source: Kreuzer Collection

mother. Pressing a key in one room, he made a bell ring in another, thirty feet away. This was the beginning of wireless communication![7]

During the spring and summer of 1895, he concentrated on improving his apparatus, most notably the coherer. Marconi tried many different kinds of metal filings, and eventually determined that a combination of 95% nickel and 5% silver produced the most sensitive device. He narrowed the space between the metal plugs and exhausted the air from the glass tube to about 1/1000th of an atmosphere, thereby increasing its reliability for signaling at greater distances. He moved his receiver to the lower floors of the house and then finally out to the garden.[8]

He was now in need of more serious funds to continue his experiments. When he approached his father for financial assistance, proof was demanded of the future possibility of signaling with his wireless. His father asked him to send an "S"; Marconi immediately did so. Suitably impressed, Giuseppe gave him 5,000 lira ($1,000) to expand his experiments.[9]

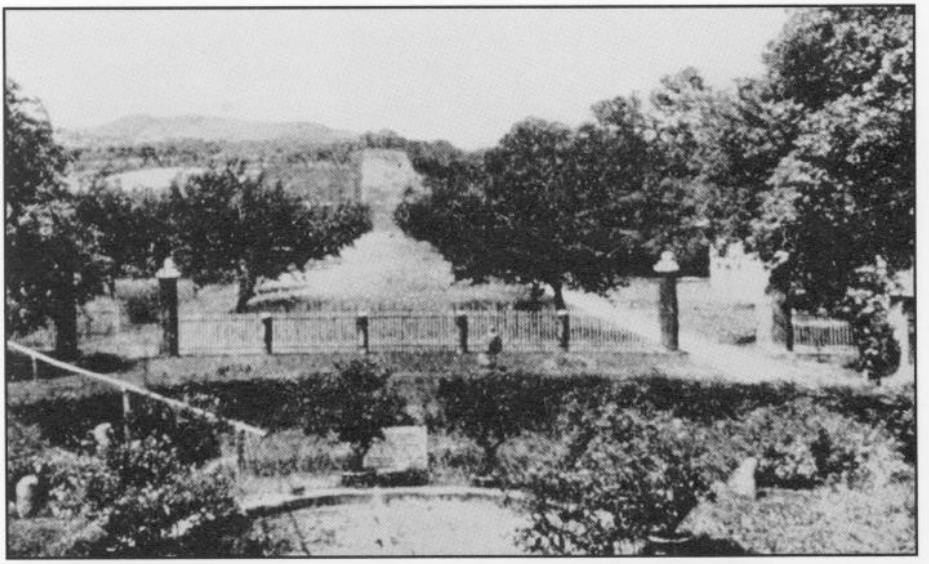


Figure 6. The grounds at the Villa Grifone at Pontecchio. Scene of the first out-doors wireless experiments.

Source: *Marconi-Master of Space*, Jacot & Collier, 1935

Guglielmo continued his experiments outside at the Villa Grifone, placing a metal plate on the ground hooked to one end of the spark coil, connecting the other to a metal cylinder on the top of a pole. The results were incredible! He could now signal for hundreds of meters with this contrivance! It was Marconi's first real antenna system. Now the electromagnetic waves could travel much further with increased signal strength.

Attempting further experiments with this grounded vertical antenna, he found that the distance over which the waves traveled was directly related to the size of the cylinder and how high it stood above the ground. For instance, if a sheet of tin one foot square was placed six feet high, he could receive signals 100 feet away. When the height was increased to twelve feet above the ground, he could receive signals 300 feet away, and finally, if he raised the height to 25 feet he received signals at 1300 feet! Marconi continued with related experiments, burying the metal plate and raising a larger metal cylinder high in the air, until he succeeded in signaling over distances of 1 1/2 miles.[10]

At the end of 1895 Marconi decided to offer his system to the Italian Ministry Of Posts and Telegraphs. They rejected his proposal on the basis that since wireless was allied to the sea, it would be better offered to the English who had greater shipping activity. It is interesting to surmise that had the Italian Navy been approached, the entire history of wireless telegraphy might have been rewritten.[11]

Figure 7. Marconi, his parents and brother Alfonso at the Villa Grifone park in Bologna just prior to his 1896 trip to England. Source: Marconi Company Archives

Annie Marconi now began, in earnest, to contact her kinfolk in Ireland with the possibility of offering the system to the British government for signaling between their lightships and the shore. Finally, Annie received an invitation from Guglielmo's cousin, Henry Jameson-Davis, an experienced business man and milling engineer. He occupied a prime position to aid Marconi in furthering his interests.

On February 2nd, 1896, 21 year old Guglielmo and his mother arrived safely in England. Full of hopes and dreams, they ran into almost immediate opposition from the customs inspectors, who looked upon the Italian youth with suspicion while they examined his "black boxes," convinced the wires and apparatus inside might be a bomb! The coherer receiver and spark transmitter were rendered useless from the rough handling they received from the customs agents.[12]

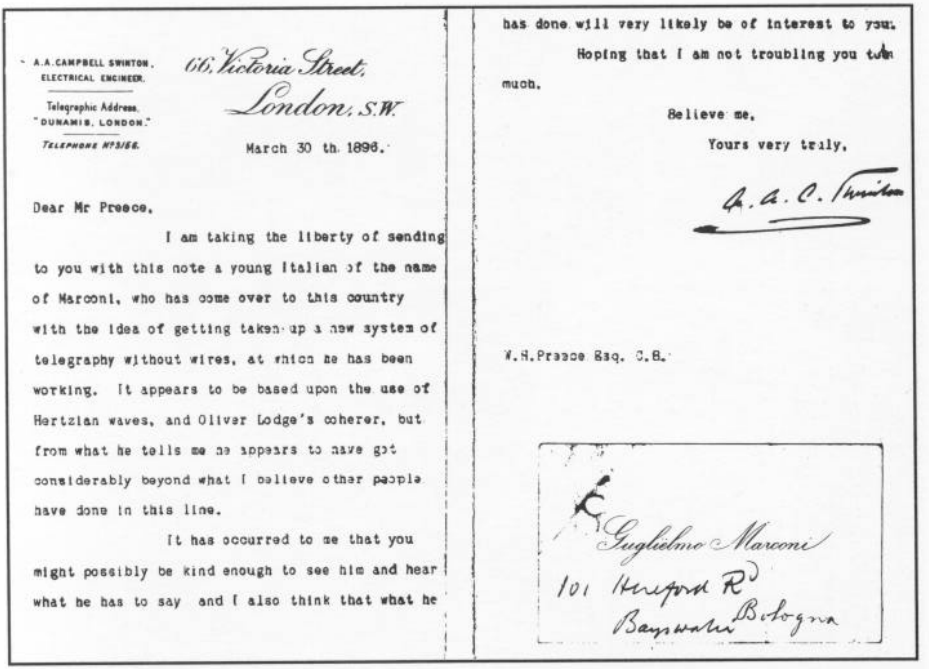
Henry Jameson-Davis met them at Victoria Station and assured Guglielmo that repairs were possible. The next week Henry busied himself with acquiring the materials needed to repair the apparatus, meanwhile developing a warm personal interest in the young man.

Figure 8. Marconi and the mysterious black box which he brought to England.
Source: Marconi Company Archives

Annie and Guglielmo rented a house in Bayswater, a quiet section of London and an appropriate place in which to continue his work. Henry Jameson-Davis introduced Guglielmo to one of the foremost patent lawyers in London who would work to establish Marconi's priority with his inventions. For four months Guglielmo labored in the preparation of his patent papers, while performing further experiments.

On June 2, 1896, Marconi deposited a provisional specification of his invention in the London Patent Office. On March 2, 1897, he followed this up with a complete specification, including eleven drawings for improvements in transmitting impulses and signals. This reached acceptance on July 2, 1897, with the granting of patent #12,039.[13]

Having established his priority in the system of wireless communication, his thoughts were next directed to the task of locating the best person to further promote his interests. It was decided that the Chief Engineer of the Post Office, Mr. William Preece, would be the person to approach; he was the man in charge of all forms of communication in England. Through a



A.A. CAMPBELL SWINTON,
ELECTRICAL ENGINEER.

Telegraphic Address.
"DUNAMIS, LONDON."

TELEPHONE No 5166.

66, Victoria Street,
London, S.W.

March 30 th. 1896.

Dear Mr Preece,

I am taking the liberty of sending to you with this note a young Italian of the name of Marconi, who has come over to this country with the idea of getting taken up a new system of telegraphy without wires, at which he has been working. It appears to be based upon the use of Hertzian waves, and Oliver Lodge's coherer, but from what he tells me he appears to have got considerably beyond what I believe other people have done in this line.

It has occurred to me that you might possibly be kind enough to see him and hear what he has to say and I also think that what he has done will very likely be of interest to you.

Hoping that I am not troubling you too much.

Believe me,

Yours very truly,

A. A. C. Swinton

W.H. Preece Esq. C.B.

Guglielmo Marconi
101 Hereford Rd
Bayswater

Bologna

Figure 9. The letter of introduction from A.A. Campbell Swinton, which Marconi presented to Mr. W. Preece, Engineer-in-Chief of the Post Office.
Source: Marconi Company Archives

fortunate coincidence, one of Henry Jameson Davis's friends was A.A. Campbell Swinton. An electrical engineer, he had witnessed some of Guglielmo's demonstrations in London and agreed to provide him with a letter of introduction to Mr. Preece.[14]

On a day in July, 1896, a young Italian man called at the G.P.O. West building and presented a letter of recommendation from A. A. Campbell Swinton to Mr. William Preece. Mr. Preece brought the youth into his office and watched as he placed on a table the contents of two large bags. Among the items was an induction coil, a Righi gap, and a small glass tube containing fine silver and nickel filings—the improved Marconi coherer.

Marconi performed numerous experiments for William Preece throughout the day. Preece was impressed, and offered Guglielmo the use of his laboratory for future experiments. More important, he promised to exercise his influence in arranging a demonstration of the wireless system for the heads of the British Postal Telegraph Department.

Marconi moved into Preece's laboratory and carried on a series of more extensive tests. The first official demonstration occurred on July 27th before

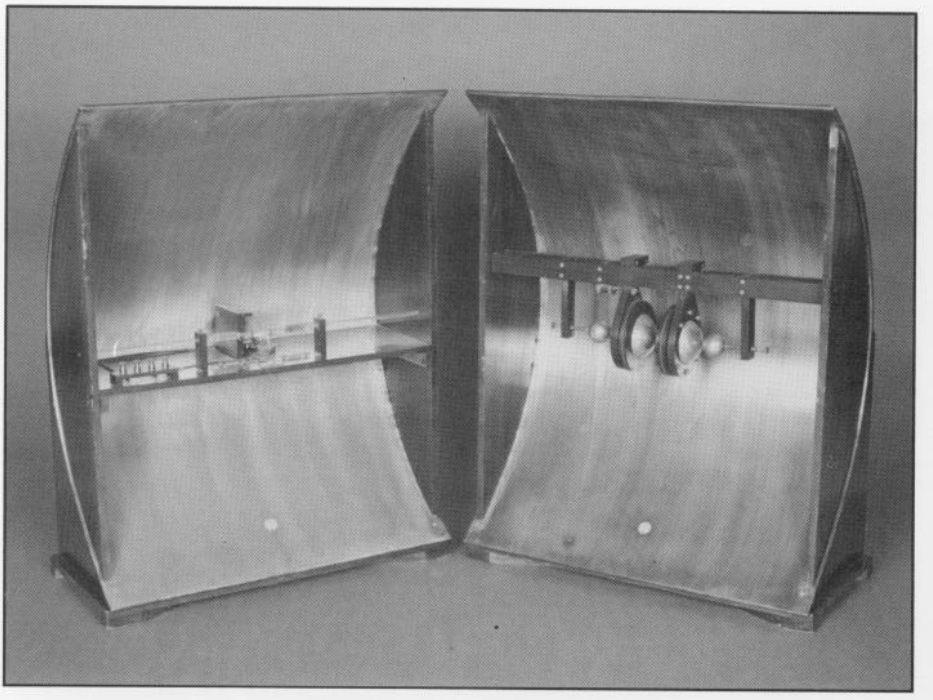


Figure 10. Parabolic transmitter and receiver at the Marconi Company Museum in Chelmsford, England. Possibly an early reproduction of Marconi's original experimental apparatus. Source: Marconi Company Archives

senior officials and engineers of the G.P.O., on the roof of the G.P.O. building in St. Martin's-le-Grand. His transmitter consisted of a Righi spark gap placed in the focal line of a parabolic reflector which was fabricated of sheet copper. His receiver combined the improved Branly coherer, a polarized relay, a Morse inker for recording, and a parabolic reflector.[15]

He was able to communicate with a station manned by members of Preece's staff on another G.P.O. building in Queen Victoria Street, near the Thames embankment, a distance somewhat less than a mile. An epoch-making day, not only was it an unqualified success for Marconi, but it marked the beginning of the British interest in wireless telegraphy.

With this initial accomplishment behind him, government support for further demonstrations was easily obtained. Marconi's first government demonstration was arranged on Salisbury Plain, near Stonehenge, on September 2, 1896. This sight was chosen because of the privacy needed for these clandestine tests. Officers representing both the army and navy were present, and a range of 1 3/4 miles was recorded.[16]

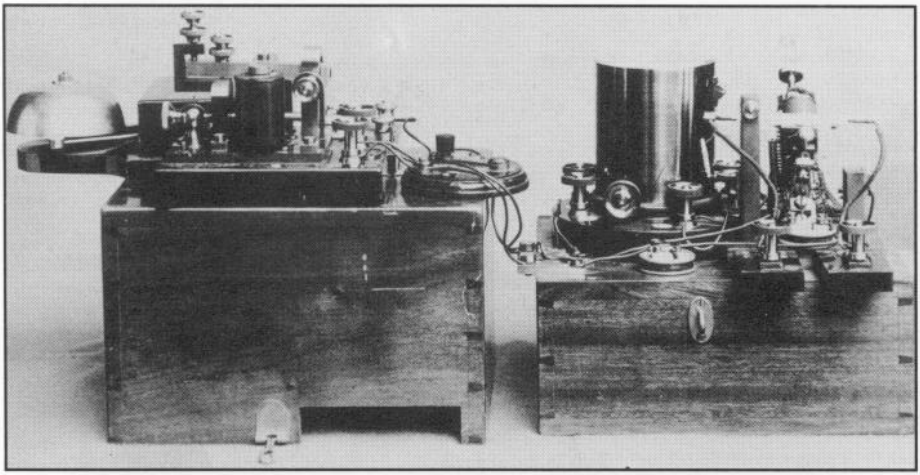


Figure 11. A detailed view inside the black box that helped make Marconi famous throughout the world. Source: Marconi Company Archives

A second series of tests was carried out in March, 1897, using the same site on Salisbury Plain, with longer antennas supported by kites. Communication was extended to distances up to 4 1/2 miles.[17] A Mr. G. S. Kemp was assigned to assist Marconi with the venture, beginning an association which was to last over 35 years, until Kemp's death in 1932. This experiment attracted considerable attention from both the press and the public at home and abroad.

The first public demonstration of wireless was held at Toynbee Hall in London during a December lecture given by William Preece. This historic demonstration verified that Marconi was developing a penchant for showmanship. He moved mysteriously around the auditorium carrying a receiver, which included an electric doorbell. Whenever Preece pressed the telegraph key, activating the spark gap, the doorbell in Marconi's hand rang. Both pieces of apparatus were enclosed in black painted boxes to further mystify the public.[18]

Having shown that his system functioned over land, he next proceeded to attempt communications over water. Here he hoped to provide even more useful applications for his wireless signals. In the spring of 1897, Marconi moved his equipment to the Bristol Channel, setting up a receiving station at Lavernock Point in Penarth, and erecting a transmitter on the Channel island of Flatholm, 3 1/2 miles away. After a few days of antenna problems, communications were finally established.

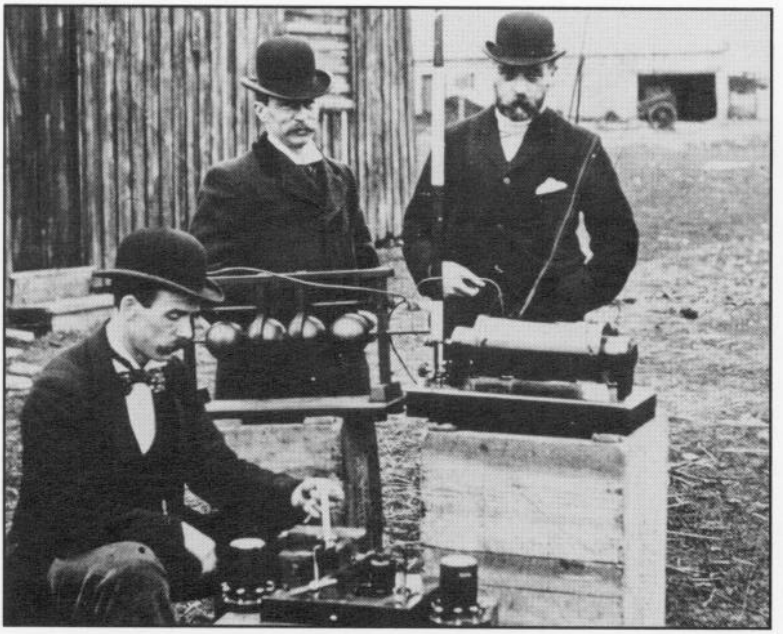


Figure 12. Post Office engineers inspecting Marconi's equipment during the Bristol Channel tests of 1897.

Source: Marconi Company Archives

On May 18 Marconi moved his transmitter to Brean Down. Using a kite to support his antenna, he was successful in signaling 8.7 miles over water.[19]

Professor Adolphus Slaby, a German electrical scientist, was also present at these tests. He submitted a very admirable report of Marconi's work for an article he contributed to the *Century Magazine* in April, 1898.

It is interesting to note that although Marconi was in possession of German patents covering his invention, about a year later patents were granted to Prof. Slaby. He had devised a different antenna system, and developed in collaboration with Count Arco the Slaby-Arco system of wireless telegraphy. In 1903 this company merged with Braun Company and Siemens-Halske to form the Telefunken company, a conglomerate which is still in business today.

William Preece gave a lecture at the Royal Institution of Great Britain on Friday, June 8, 1897, entitled "Signalling Through Space Without Wires". In this lecture he described his own system of wireless telegraphy using an induction method, comparing it to Marconi's use of Hertzian Wave telegraphy. He extolled Marconi's system and supported Marconi's use of Branly's coherer and Righi's spark gap, ending his lecture with this:

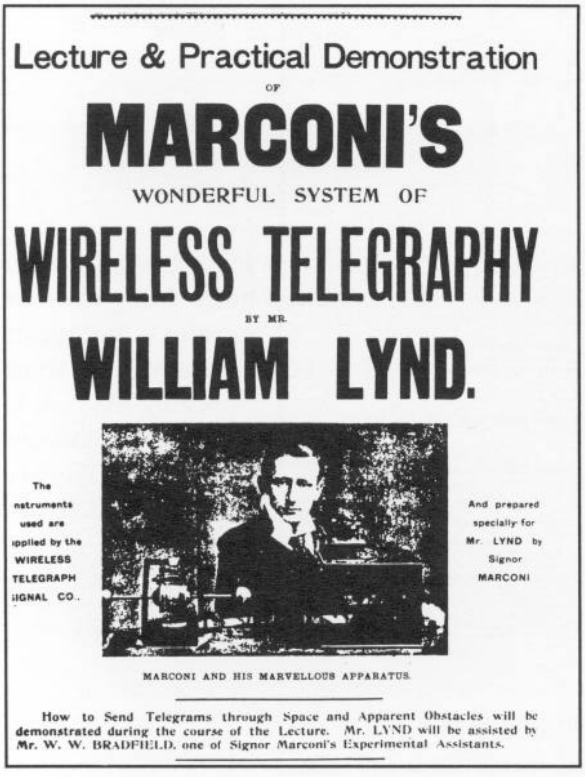
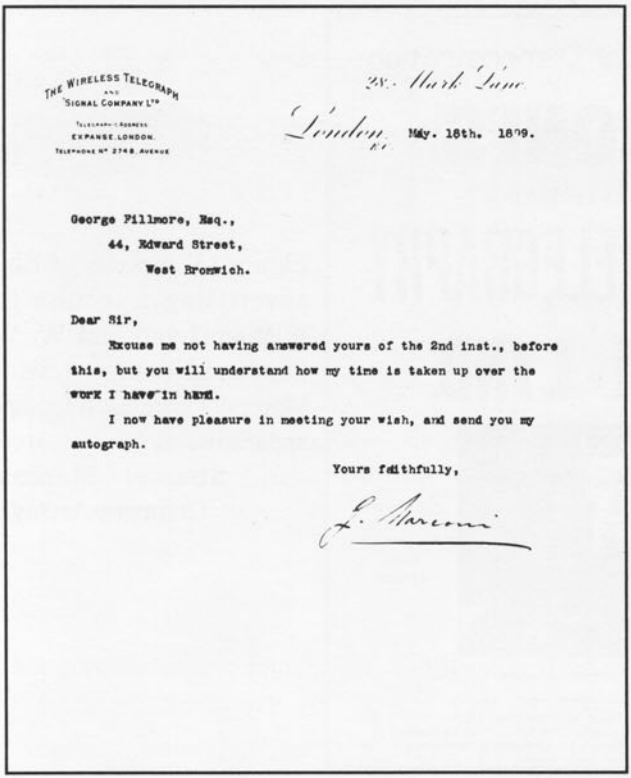


Figure 13. A poster of 1897 advertising a lecture by William Lynd and W. W. Bradfield demonstrating Marconi's wireless telegraph apparatus.

Source: Marconi Company Archives

> It has been said that Mr. Marconi has done nothing new. He has not discovered any new rays; his transmitter is comparatively old; his receiver is based on Branly's coherer. Columbus did not invent the egg, but he showed how to make it stand on its end, and Marconi has produced, from known means, a new electric eye, more delicate than any known electrical instrument, and a new system of telegraphy that will reach places hitherto inaccessible. There are a great many practical points connected with this system that require to be threshed out in practical manner before it can be placed on the market, but enough has been done to prove its value, and to show that for shipping and lighthouse purposes it will be a great and valuable acquisition.[20]

In April, 1897, Marconi was approached by Henry Jameson Davis who proposed that a company be formed to develop and exploit his invention. Marconi resisted, feeling that he owed much to the G.P.O. for the valuable support given him in the early days. He had reached a point, however, where considerable capital would be necessary if he was to continue progress with wireless. Therefore, Marconi informed Preece of his requirements; he needed about £25,000 to develop and patent his system.[21]



THE WIRELESS TELEGRAPH AND SIGNAL COMPANY LTD

TELEGRAPHIC ADDRESS EXPANSE, LONDON. TELEPHONE No. 2748 AVENUE

28, Hatton Garden, London, E.C. May. 18th. 1899.

George Fillmore, Esq.,
44, Edward Street,
West Bromwich.

Dear Sir,

Excuse me not having answered yours of the 2nd inst., before this, but you will understand how my time is taken up over the work I have in hand.

I now have pleasure in meeting your wish, and send you my autograph.

Yours faithfully,

G. Marconi

Figure 14. A letter-head from the first wireless telegraph company in the world, signed by Marconi for an autograph collector. Source: Kreuzer Collection

Although William Preece made a recommendation to his superiors to offer Marconi £10,000 for his patent, the government refused and no offer was made. Tired of kicking his heels on the doorstep of the British Treasury, Marconi relented, and on July 20, 1897 the first wireless company was formed: The Wireless Telegraph and Signal Company, Ltd.[22]

The Company paid Marconi £15,000 in cash, plus 60,000 of the 100,000 shares of £1 each. This comprised the authorized capital for his patent rights, of which all were relinquished excepting the Italian rights to his system. The balance of 40,000 shares was to be put on the market for public subscription. The cash to purchase these shares was subscribed mostly by the Jameson and Davis families, with some capital coming from family members in Scotland. Henry Jameson-Davis, representing the interests of his family, became the first managing director.[23]

Guglielmo received an invitation from the Italian government to go to Spezia and Rome and give a demonstration of his wireless telegraph system. Marconi arrived during July, 1897, and immediately set about assembling his receiving apparatus on a tugboat. The transmitter was located on the inner shore of the Gulf of Spezia with a vertical antenna wire 78 feet high ending in a zinc

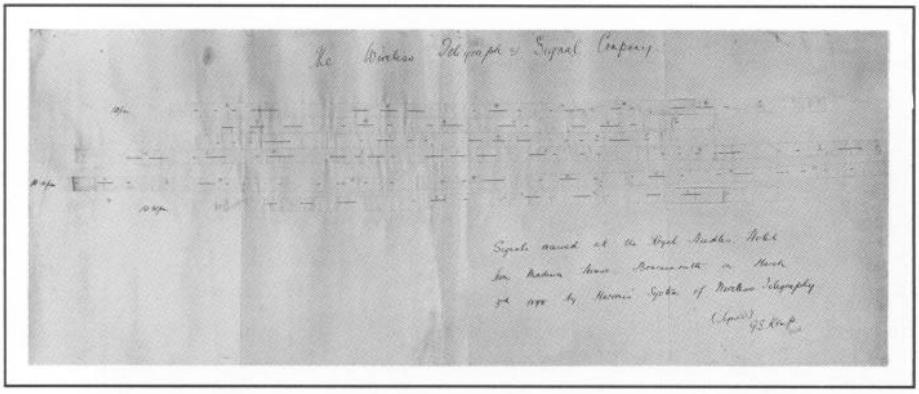


Figure 15. A record of the original signals received at the Royal Needles Hotel from the Madiera House, Bournemouth on March 3, 1898, signed by G.S. Kemp.
Source: Marconi Company Archives

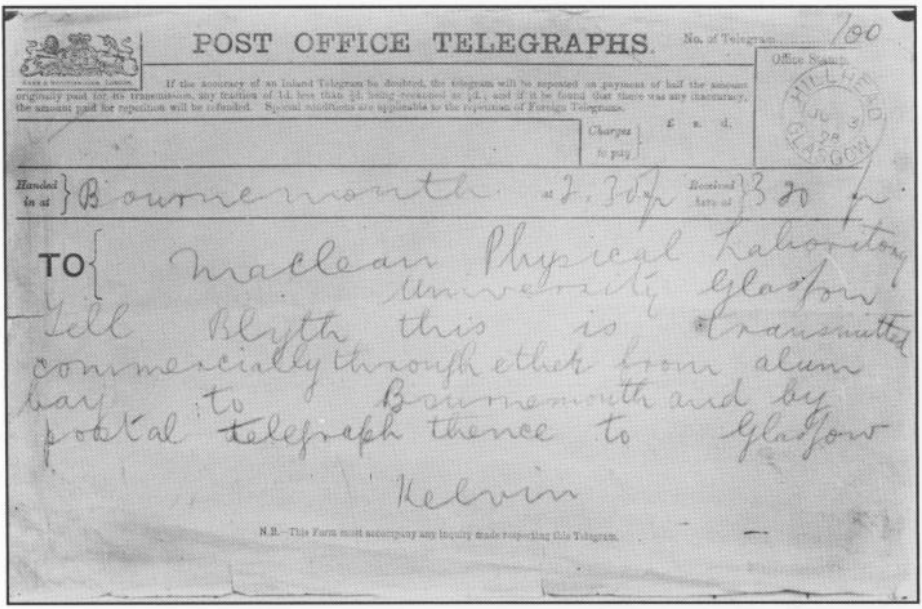
plate, while the receiving antenna was 48 feet high, grounded in the water of the bay.[24]

The first signals were received at a distance of 2 1/2 miles, but when the transmitting antenna was raised to 90 feet he extended his reception to eight miles. This was the first time a signal was received using a moving receiving set.

The receiver was then transferred to the Italian warship, and the aerial on the receiving station was raised to 90 feet, while increasing the transmitter antenna to 111 feet. With these changes Marconi was successful in achieving signals up to 11 1/2 miles from shore, the greatest distance he had ever realized.[25]

With his work completed at Spezia, he took his apparatus to Rome and performed a successful demonstration for the king and queen of Italy. As a result, it was announced that Marconi wireless apparatus was to be adopted by the Italian Navy.

Upon Marconi's return to England he was forced to attend to the final details of his company's formation. Not only busy with his experiments, he was confronted with the rigors of establishing a commercial plan for his system of wireless telegraphy. The inception of his company marked the end of any official support from the British Post Office. Although relations were strained, he always remained close friends with William Preece.



POST OFFICE TELEGRAPHS. No. of Telegram 190

Office Stamp: HILLHEAD JU 3 2PM GLASGOW

Handed in at: Bournemouth at 2.30 p

Received here at: 3 20 p

TO: Maclean Physical Laboratory University Glasgow

Tell Blyth this is transmitted commercially through ether from alum bay to Bournemouth and by postal telegraph thence to Glasgow

Kelvin

N.B.—This Form must accompany any inquiry made respecting this Telegram.

Figure 16. The first paid wireless telegram sent by Lord Kelvin to his chief assistant on June 3rd, 1898, from the Royal Needles Hotel at Alum Bay.
Source: Marconi Company Archives

In September, 1897, the British Post Office began to perform their own experiments at Dover, without informing Marconi. He was upset about not being invited to participate in the experiments, which were made using his apparatus. After the tests produced disappointing results, an attempt was made to secure Marconi's participation, but he declined.[26]

The first goal of the new company was to establish some permanent wireless stations to be used for public demonstrations and trials. The first was constructed in November at the Needles Hotel, Alum Bay, on the Isle of Wight. The following month, tests of ship-to-shore communications were carried out using a small steamer named *The Solent*. Messages were sent at distances of 18 miles.[27]

In February, 1898, a companion station was erected at the Madiera Hotel in Bournemouth, and on March 3, successful communication was established fourteen miles away. The antennas were 120 feet high and the standard 10" induction coil was used.[28]

On June 3, 1898, Lord Kelvin visited the Needles station. It was then that Kelvin sent the first wireless telegram, to his chief assistant in the Physical Laboratory of the University of Glasgow. Kelvin insisted on donating a

Figure 17. An early shipboard wireless station aboard the lightship *Tongue* in 1900. It used the Marconi coherer receiver and the 10" spark coil.

Source: Marconi Company Archives

payment of one shilling for the service, giving it the distinction of being the first paid Marconigram. The station at Bournemouth was moved in September (because of trouble with the hotel management) to the Haven Hotel in Poole, where it remained a prominent experimental center until it was finally closed in 1926.

The first income the Wireless Telegraph and Signal Company was to receive came in the way of an assignment from the Dublin Daily Express newspaper. Marconi was commissioned to relay the progress of the boats in the 1898 Kingstown Regatta. This novel experiment proved a complete success. Developments were reported to a newspaper on shore during the race, and a special edition was published and sold on the streets.

Seven hundred messages were sent in all, ranging in distance from ten to 25 miles. Similar demonstrations began to be reported in newspapers all over the world, producing a profound effect on the public's perception of wireless.[30]

Trinity House, a corporation in charge of lighthouses and lightships, commissioned Marconi to install his apparatus at the South Foreland lighthouse at Dover and on the *East Goodwin Lightship*, anchored twelve miles from shore.[31]

On Christmas eve of 1898, with George Kemp at the key, two-way communication was established. This winter was particularly severe, with many storms moving up the coast. The ship was constantly tossed about, subjected to high winds and very heavy seas. In early January a huge wave ripped away a section of the ship's bulwarks. The damage was reported immediately to the South Foreland lighthouse; wireless had finally been used to report an accident at sea.[32]

Kemp instructed the lighthouse men in the operation of the transmitter and receiver, as well as Morse code. This proved a time-consuming task, but finally on January 9 he was able to leave after spending 22 days on board. On March 17, 1899, a decidedly foggy day, the steamship *Elbe* went aground on the Shoals. The East Goodwin heard the steamer's incessant whistles and summoned help by way of the wireless on board.The entire crew of the grounded steamer was rescued, as well as more than a quarter of a million dollars in goods. This was the first time wireless was used to save lives as well as property.[33]

Sir Ambrose Fleming commented, "Marconi was eminently utilitarian. His predominant interest was not in purely scientific knowledge per se, but in its practical application for useful purposes."[34]

In March, Guglielmo was anxious to establish communication between France and England, across the English Channel. He requested permission from the French government to erect a wireless station at Wimereux, France. The French consented, and on March 27, 1899, after a few weeks of construction, Marconi was ready for the test.[35]

With French dignitaries in attendance, Marconi sent and received messages to the South Foreland Lighthouse in England immediately, and with no problems, greatly impressing his audience. The English Channel had been bridged by wireless!

Upon the completion of the tests across the English Channel, Marconi decided to turn his attention to America. He had been invited by James Gordon Bennett, owner of the New York Herald, to report the America Cup Races by wireless. On September 11, 1899, Marconi sailed from Liverpool, arriving in New York on September 21. Greeted with some fanfare due to the Herald's prior announcement, Marconi wasn't the least bit intimidated by the tall buildings. What did upset him, though, was the discovery that a trunk was missing from his many pieces of luggage—the important one containing the coherers!

After frantic searching it was found that the trunk had been loaded on the wrong ship in Liverpool, and was now in Boston. W.W. Bradfield, one of

Marconi's assistants, went to Boston and brought the vital trunk back.[36] On September 29, 1899, the equipment was in place and the first United States shipboard wireless message sent by Marconi was transmitted from the *S.S. Ponce* to a shore station set up on a tall building at Navesink Highlands, New Jersey.

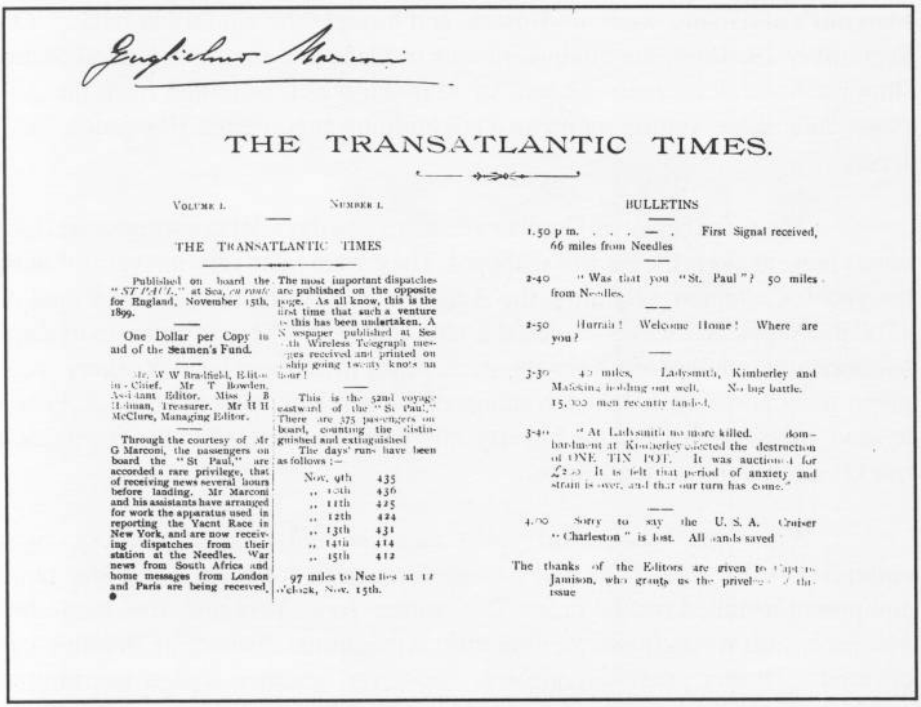
The races began on October 16 after a few days delay owing to the light winds present along the eastern seaboard. They were relatively uneventful with the yacht *Columbia* retaining the America cup. Marconi had sent a total of 1200 messages and was considered a national hero.[37] The advantages of ship-to-shore communications were apparent. Many prominent New Yorkers were given an opportunity to take advantage of the wireless on board the *S.S. Ponce* to send messages back to the big city, and were also treated to the latest stock market quotations on Wall Street.

With the successful yacht races behind him, Marconi was commissioned by the U.S. Navy to perform tests for them using the same equipment installed for the races. The cruiser *New York* and the battleship *Massachusetts* were chosen for this task; a maximum distance of 36 miles was covered. During the experiment, however, another station transmitted messages at ten-minute intervals, rendering the Morse inker tapes completely unintelligible due to interference.[38]

This was of immense importance to Marconi, as it demonstrated a main weakness in his system, the inability to separate multiple signals. He had been working on selective tuning, but was far from finished and hadn't filed any patents for his apparatus. The Navy looked upon these tests as failures, so Marconi left the U.S. without any orders for his wireless telegraph instruments.

Before he left, however, Marconi issued a prospectus to form a company for the purpose of purchasing the American patent rights held by the English company. Receiving a favorable response, the American Marconi Telegraph Company was organized on November 22, 1899, under the laws of the state of New Jersey. Its authorized capital was $10,000,000, covered by the issuance of two million shares of stock with a par value of $5.00 each. This company was the first of many foreign subsidiaries which Marconi was to form.[39]

Upon completion of the U.S. Naval demonstrations, he packed up and headed back to England on the *S.S. St. Paul*. While on this return trip, when 66 miles from the Needles station, he received satisfactory signals. He was able to record the news of the day, including progress of the South African war. He authorized the captain to print the news on a single sheet, calling it the "Transatlantic Times." He sold it to the passengers at $1 per copy, with the



Guglielmo Marconi

THE TRANSATLANTIC TIMES.

VOLUME I. NUMBER I.

THE TRANSATLANTIC TIMES

Published on board the "*ST PAUL*," at Sea, *en route* for England, November 15th, 1899.

One Dollar per Copy in aid of the Seamen's Fund.

Mr. W W Bradfield, Editor-in-Chief. Mr T Bowden, Assistant Editor. Miss J B Hannan, Treasurer. Mr H H McClure, Managing Editor.

Through the courtesy of Mr G Marconi, the passengers on board the "St Paul," are accorded a rare privilege, that of receiving news several hours before landing. Mr Marconi and his assistants have arranged for work the apparatus used in reporting the Yacht Race in New York, and are now receiving dispatches from their station at the Needles. War news from South Africa and home messages from London and Paris are being received.

The most important dispatches are published on the opposite page. As all know, this is the first time that such a venture as this has been undertaken. A Newspaper published at Sea with Wireless Telegraph messages received and printed on ship going twenty knots an hour!

This is the 52nd voyage eastward of the "St. Paul." There are 375 passengers on board, counting the distinguished and extinguished

The days' runs have been as follows :—

Nov. 9th	435
,, 10th	436
,, 11th	425
,, 12th	424
,, 13th	431
,, 14th	414
,, 15th	412

97 miles to Needles at 11 o'clock, Nov. 15th.

BULLETINS

1.50 p m. . . . — . First Signal received, 66 miles from Needles

2-40 " Was that you "St. Paul"? 50 miles from Needles.

2-50 Hurrah! Welcome Home! Where are you?

3-30 40 miles, Ladysmith, Kimberley and Mafeking holding out well. No big battle. 15,000 men recently landed.

3-40 " At Ladysmith no more killed. Bombardment at Kimberley effected the destruction of ONE TIN POT. It was auctioned for £2-0. It is felt that period of anxiety and strain is over, and that our turn has come."

4.00 Sorry to say the U. S. A. Cruiser "Charleston" is lost. All hands saved

The thanks of the Editors are given to Capt. Jamison, who grants us the privilege of this issue

Figure 18. An original copy of the "Transatlantic Times" signed by Marconi while on board the *S.S. St. Paul.* Source: Kreuzer Collection

proceeds going to the Seamans' Fund. This was the first time a newspaper had been printed on board a ship with the help of wireless.[40]

By the end of 1899 communication between ships and land stations using distances of 80 to 100 miles had become an accomplished fact. Without contracts, however, there was no revenue for the Marconi Company. By 1900, shipping companies, realizing the value and importance of the discovery, began to install wireless on their ships.

Maclaurin records in his book, "Marconi had decided in 1900 that he would not sell apparatus outright, but only lease it. This decision covered all types of wireless equipment; when Fleming wrote Marconi to ask if his valve could be put on sale, Marconi replied; "....your valve is likely to become a very valuable receiver for long distance wireless, and I wish if possible to keep the monopoly of these experiments to ourselves." Marconi's leasing arrangements to ships provided for a certain number of messages per month without charge, plus a standard rate per word above this maximum. The company trained and furnished wireless operators who remained on the company payroll. Marconi reasoned that, if the equipment were sold outright, the price charged would not

Figure 19. A colorful British Marconi Company stock certificate issue in 1909 and signed by Alfonso Marconi, one of the directors.
Source: Kreuzer Collection

be enough to support any effective research and engineering. And he was determined to perfect his system of radio communications by continuing his experiments."[41]

In the United States, however, Marconi found himself compelled to sell rather than lease wireless apparatus, but he imposed many restrictions. The U.S. Navy would have to pay a substantial flat royalty each year and equipment had to be purchased at current market prices, including duty. He also required messages to be accepted for relay from Marconi equipped merchant vessels and commercial Marconi stations. Marconi equipment was not to be used for communication with any rival system except in an emergency or when working with another naval vessel. The U. S. Navy refused to agree to these conditions, and sought to work with other companies such as Slaby-Arco and the Deforest Wireless Company. The Marconi Company lost many lucrative contracts in the U.S. because of its stance on this issue.

At the annual meeting of The Wireless Telegraph and Signal Company on February 23, 1900, a resolution was adopted which changed the name of

the company to "Marconi's Wireless Telegraph Company, Ltd.". On April 25 (Marconi's twenty-sixth birthday) The Marconi International Marine Company was formed to establish marine wireless telegraphy on a sound commercial basis throughout the world. Its main purpose was to equip and manage the maritime wireless activities across the seas.[42]

In 1898 Marconi had introduced the "Jigger", or oscillation coil, whereby the primary was wired in the aerial circuit, with the secondary connected to the coherer circuit of the receiver. Using various taps, this coil helped match the antenna to the receiver. The first "syntonized" tuned transmitter designed by Marconi was constructed in 1899 following arduous experimentation lasting over a year. It consisted of an oscillation coil transformer using a spark gap and a Leyden jar condenser in the primary, while the secondary was connected to an adjustable inductance in the aerial circuit. (Also see Fig. 23.)

On April 26, 1900, Guglielmo Marconi filed a provisional specification for a patent on selective tuning. It incorporated tuned coupled circuits which enabled the wireless receiver to tune out unwanted stations causing interference with the reception of the intended transmitter. The Marconi "Four Sevens Patent" (#7,777) controlled the use of syntonic wireless telegraphy and was granted in 1901.[43] Sir Oliver Lodge had also been doing research along these lines and eventually sold his rights to the Marconi Company. This patent put the Marconi Company very close to a monopoly of syntonic wireless telegraphy in England and America.

In July, 1900, the British Admiralty contracted for the installation of the Marconi system in 26 warships and six coast stations. The financial terms were settled in November, 1901, providing the Marconi Company with £100 per set as an annual royalty for a period of ten years.[44] In September, 1901, Lloyd's of London placed an order for ten signaling stations to be fitted with wireless - primarily for maritime communication. Marconi received greater pleasure from the prestige gained by the order than any financial benefit.[45]

THE ATLANTIC IS CROSSED!

Ever since Marconi bridged the English Channel linking England and Europe by wireless, his mind was occupied by a much greater challenge—to send wireless signals across the Atlantic Ocean.

For this purpose, John Ambrose Fleming was brought in to design and build the transmitter because of his skill in working with high voltage alternating current systems.[46] R.N. Vyvyan was chosen to take charge of the

construction of the station and assist Fleming in obtaining the necessary machinery. A spot near Land's End, at Poldhu, was chosen for the transmitter site, and work was begun in December, 1900. After a major setback, caused by the collapse of the immense antenna system, it was replaced by a large fan-type aerial, and the construction at Poldhu was completed by February, 1901.[47]

Marconi then turned his attention to the other side of the Atlantic, and proceeded to erect a similar antenna system on Cape Cod, near South Wellfleet, Mass. The same fate awaited this mammoth structure; it too was destroyed by a storm in October, 1901, prior to Marconi's scheduled arrival for the tests. It was decided to use a balloon or kite to raise the antenna, and move the site from Cape Cod to St. John's, Newfoundland, where the distance was not so great.

Marconi and his entourage of G.S. Kemp and P.W. Paget arrived in secrecy at St. John's on December 6, 1901. Guglielmo chose to keep his tests confidential in case they weren't successful. He would not brag beforehand about what he might do - he was careful to give his best shot first, and only then announce his victory.

He chose a site next to the Cabot Memorial Tower, an unused army barracks on a high point overlooking St. John's, known as Signal Hill. The first few days were spent hauling in the shipping trunks which contained gas cylinders, balloons, kites, receiving apparatus and sheets of zinc for the earth system. The next chore was digging in the frozen earth to install the zinc-plate ground system.[48]

It was a cold and damp place, so they worked in shifts, coming in frequently to warm themselves by the coal stove. It was agreed that the operators at the Poldhu station would begin sending the letter "S" during a three-hour period of transmission at 12 noon on the 11th day of December. This letter was chosen not only because it could easily be recognized, but also for the lack of a suitable sending key. They were forced to use a ponderous electrical switch to make and break the circuit. Also, the transmitter was not built to withstand the full power of the supply, and if dashes were sent, the generator and other components might have overheated excessively.[49]

Early in the day they finished wiring up the receiver and then attempted to raise a balloon to lift the heavy aerial wire, but a gale force wind ripped it loose from its moorings. The wind continued the next day and it was decided to try using a kite to raise the antenna system, which now would be untuned, owing to the varying height of the kite. He was forced to use the Italian Navy coherer, developed by Luigi Solari, and abandon the Morse recorder in favor of a headphone. Marconi and his crew assembled the new apparatus, raised the cumbersome kite up about 400 feet in the air, and waited for noon.[50]

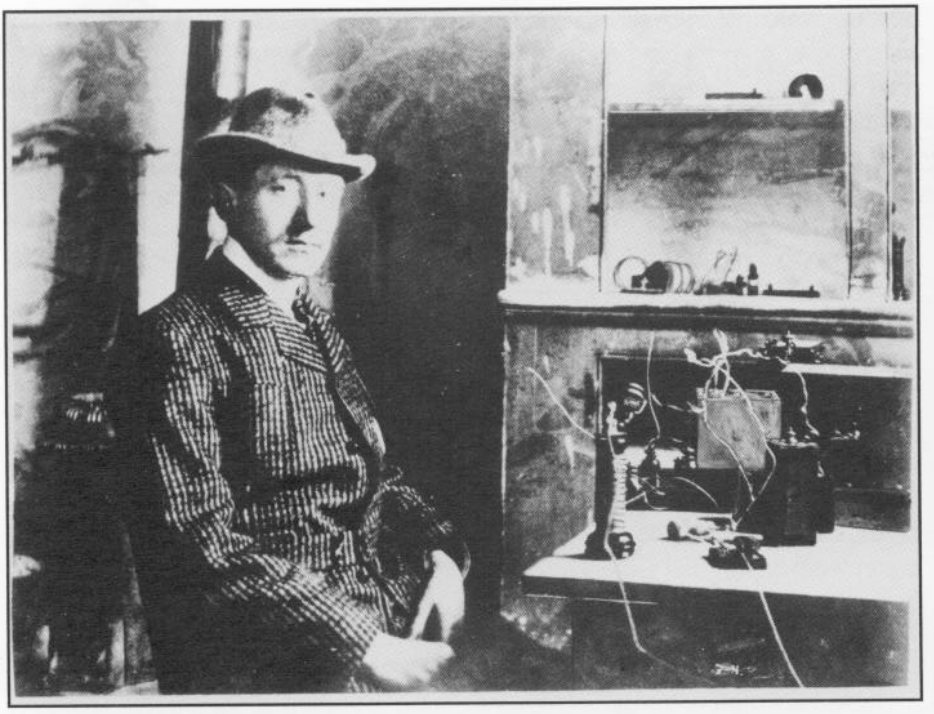


Figure 20. Guglielmo Marconi sitting with his receiving set in St. John's, Newfoundland, on December 12, 1901. Source: Marconi Company Archives

At precisely 12 noon Marconi picked up the headphone and placed it to his ear. After a few minutes he handed it to Kemp and asked if he heard anything. Kemp exclaimed that he too had heard it—the letter S—three dots! They continued to receive the signal intermittently for the rest of the day and part of the next. Kemp's diary records for history the various times of reception and signal strengths. [51]

The date of December 12, 1901, has become one of the major landmarks in the development of wireless communication. After much contemplation Marconi decided to release the news to the media concerning his triumph over the Atlantic—2,170 miles! The reaction of the public to the feat was enthusiastic, but there were many scientists who doubted this feat had actually occurred.[52]

After the successful test had been made public, the Anglo-American Telegraph Company threatened legal proceedings against Marconi if he continued to receive signals in Newfoundland. Since they held the sole rights for telegraph traffic on the island, Marconi decided to request another

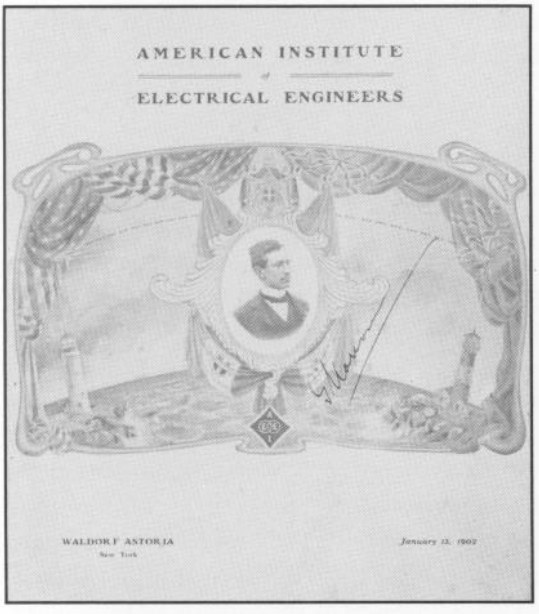


Figure 21. Cover of the menu presented at the AIEE Dinner where Marconi was the guest of honor following his successful transatlantic signal. Marconi autographed this one.
Source: Kreuzer Collection

opportunity in Ottawa. There the Canadian government offered a subsidy of £16,000 towards the erection of a wireless station on the coast of Canada, but with one condition; the rate for wireless messages could not exceed ten cents a word. Marconi gratefully accepted and began planning a high-power station to be erected near the town of Glace Bay on Cape Breton Island, Nova Scotia.[53]

Before returning to England, Marconi was invited to be the guest of honor for the American Institute of Electrical Engineers annual dinner at New York City's Waldorf Astoria Hotel. The affair was arranged with only 48 hours notice owing to the unavoidable uncertainty of Marconi's arrival from Canada, and his intention of sailing almost immediately from New York after the dinner.[54]

It was truly a gala affair, with the hall including "a tablet at each side, one labeled Poldhu and the other St. John's, with a string of fairy lights joining the two tablets, blinking on and off in the dot-dot-dot of the Morse letter "S." Marconi's name was spelled out in lights above the high table which was backed by the Stars and Stripes. More lights supplemented the floral decorations, where the final touch was the setting down of ice stuck with tiny frozen telegraph poles."[55]

Such was the appropriate greeting Marconi received from the Americans after his triumph over the Atlantic. Attended by over 300 members and their wives, many dignitaries were present, including Charles Steinmetz, Elihu Thomson, Alexander Graham Bell, Mrs. Thomas Edison, Michael Pupin

and Frank Sprague. Telegrams containing congratulations were received from Nikola Tesla and Thomas Edison, who were unable to attend the hastily planned reception.

Ten days later Marconi sailed to England to confer with the board of directors concerning which direction the company should take following his great accomplishment. His initial plan was to put to rest the doubts regarding the actual reception of his transatlantic signal. A month to the day from his return to England, he again sailed for America. This time he brought his new syntonic receiver for use in receiving the signals from Poldhu.

Aboard the *S.S. Philadelphia*, equipped with an antenna 150 feet high, Marconi and his assistants, R.N. Vyvyan and C.S. Franklin, carried out their experiments. The receiving equipment included a Morse ink recorder to provide a permanent record of the messages received at the station. Complete messages were received at a distance of 1551 miles, while signals were detected up to 2,099 miles, just short of the distance from Poldhu to Newfoundland. The demonstration was witnessed by the captain and the chief officer, as well as many passengers who showed an interest. The captain signed the paper tapes as further proof that signals had indeed been received at the distance claimed![56]

When the ship docked at New York, there were hordes of reporters awaiting his arrival. He calmly handed them the signed tapes with the comment, "This merely confirms what I have previously done in Newfoundland. There is no longer any question about the ability of wireless telegraphy to transmit messages across the Atlantic."[57] Within a year he would be described as the most interviewed man in the world.

The completion of the transatlantic tests signaled an end to Marconi's early experiments. We will now examine the formation and development of the various wireless telegraph factories in the U.K. and North America.

THE MANUFACTURING PLANTS OF THE MARCONI COMPANY

THE CHELMSFORD, ENGLAND, FACTORY

Shortly after his arrival in England, Marconi began assembling apparatus for experimentation in his Bayswater residence. Later, he was to continue his work as he moved to subsequent dwellings in the London area.

Until early 1899 the ground floor room of the Haven Hotel station at Poole served as the main laboratory and manufacturing facility. W. J. Baker, in

FERDINAND ERNECKE
Mechanische Werkstätten
mit Elektromotorenbetrieb.
BERLIN S.W., Königgrätzer Strasse No. 112.
Apparat zur Demonstration
der
Telegraphie ohne Draht
nach Marconi.
Fig. 1.
Für Schulen und öffentliche Vorträge.

Figure 22. The earliest known trade catalog dedicated to wireless apparatus. It promotes the Marconi system of wireless, and was donated to the Franklin Institute Library in October, 1897.

Source: Kreuzer Collection

A History of The Marconi Company writes, "A visitor to the station in 1899 records that in the main laboratory he found two of the earliest employees, the brothers Cave, at one table making coherers; at another, P.W. Paget was winding receiver chokes and at a third Marconi himself was busy fitting V-plug gaps into an experimental coherer. Outside, along the foreshore, Dr. Erskine Murray was conducting parabolic mirror reflector tests, using centimetric wavelengths."[58]

In due course Guglielmo was ready to begin commercial production of his system. Foremost, he needed to acquire a building in which to set up his own manufacturing facilities. Searching the area surrounding London, he decided on the Essex town of Chelmsford, about 35 miles away. Chelmsford had a number of advantages. Besides being close to London, cost of land was reasonable and the wide, flat, undeveloped countryside seemed highly suited for wireless experiments. It was also near the Port of London, which handled a considerable amount of shipping. This could lead to a potential source of income for the fledgling company.

In December, 1898, a former silk factory and furniture warehouse on Hall Street became the world's first wireless factory. Although he occupied the

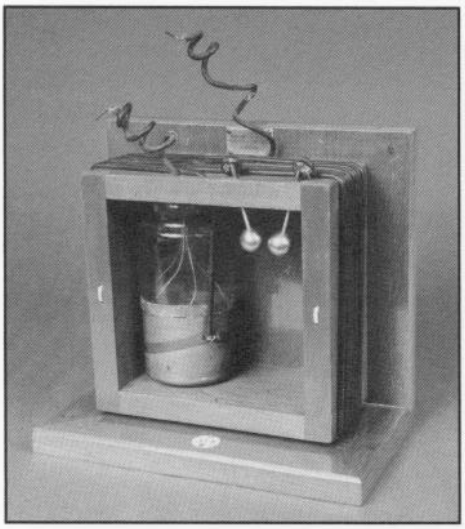


Figure 23. This is one of the original oscillating circuits employed by Marconi in 1899 which led to the introduction of tuned circuits in both transmitters and receivers. The square wood frame carries two windings. One of these is in series with the Leyden jar and spark gap, the balls of which were connected to the terminals of the induction coil. The other winding consists of a single turn connected between the aerial and ground. This arrangement provided more sustained oscillations and helped greatly to reduce the mutual interference previously experienced. It formed the basis of the famous "Four Sevens" patent (#7777) of 1900. Source: Marconi Company Archives

building in November, it wasn't until January 25, 1899, that the lease was signed. The warehouse was empty and it took several months to acquire the necessary machine tools and design the manufacturing arrangement. The Directors' Report dated December 19, 1899, stated: "The machinery and plant have been installed and the works are in running order...."[59]

Approximately 40-50 people were employed. The men worked on the ground floor in the machine shop and assembly area. The women were upstairs in the coil winding and condenser shop, where they insulated and lacquered the windings and assembled the induction coils. The items manufactured included the coherer, polarized relay, induction coil, Righi spark gap and tuned circuit. They were supervised by Mr. E.T. Priddle, the first Works Manager. In July

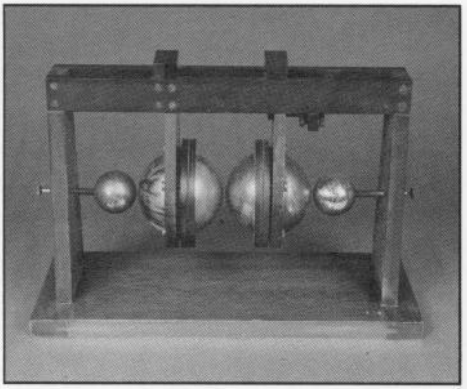


Figure 24. A Righi spark gap, developed by Augusto Righi and improved by Marconi. Dating from 1899, it was one of the first items manufactured by Marconi at Chelmsford.
Source: Marconi Company Archives

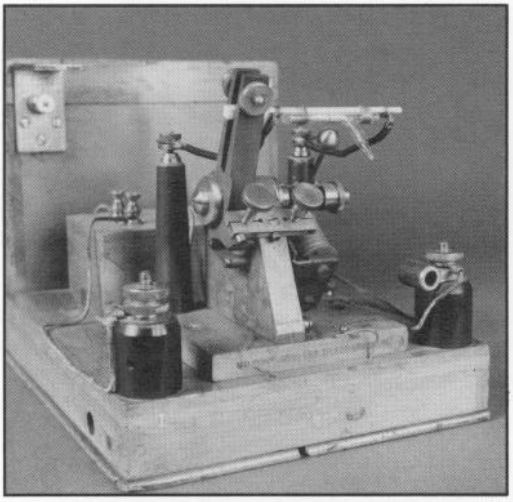


Figure 25. A detailed view of the coherer/decoherer assembly. Various styles were produced, using both wood and ebonite bases. This was standard ship's wireless equipment for the reception of telegraphic messages from 1898-1905. Source: Marconi Company Archives

Dr. Erskine Murray left the experimental laboratory at the Haven Hotel in Poole to take charge of the technical work in Chelmsford.[60] By September, 1899, a station was in place at the factory; it was able to receive signals from the Wimereux station in France, 85 miles away. [61]

Although the Wireless Telegraph and Signal Company in 1900 had a technical staff of only 17 engineers, Marconi always had a way of surrounding himself with very knowledgeable men. Included among them were the famous personages W.W. Bradfield, W.H. Eccles, Andrew Gray, C.S. Franklin, J.A. Fleming, G.S. Kemp, Dr. Erskine Murray, H.M. Dowsett, H.J. Round and R.N. Vyvyan.[62] (See Fig. 32)

The first significant order obtained by the Hall Street works was the Admiralty contract of July 4, 1900. They were requested to supply 32 sets of

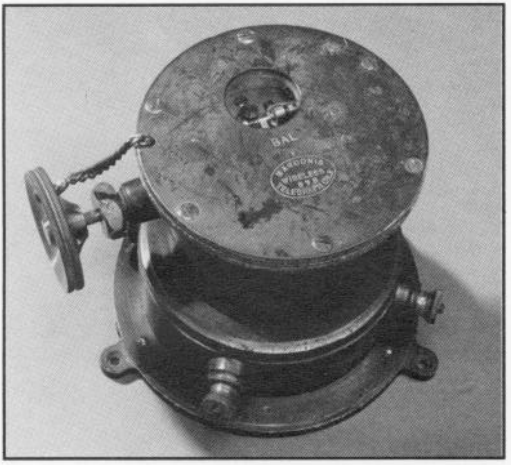


Figure 26. A polarized relay, dating from about 1900 and used on the coherer receiver. With this device in the receiving circuit it was possible to record wireless signals on a Morse inker.
Source: Kreuzer Collection

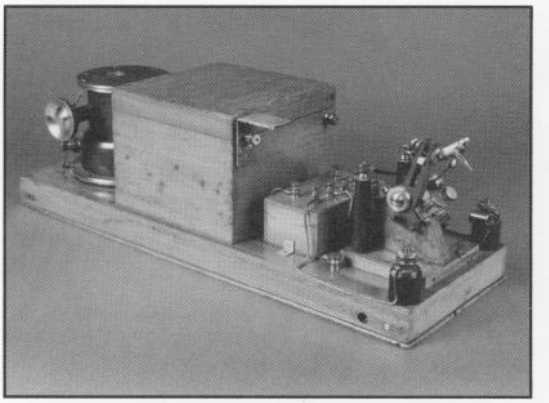


Figure 27. A complete coherer receiver, this style was used both on shipboard and in land stations, circa 1900. It was enclosed in a metal box to shield it from the station's spark transmitter.

Source: Marconi Company Archives

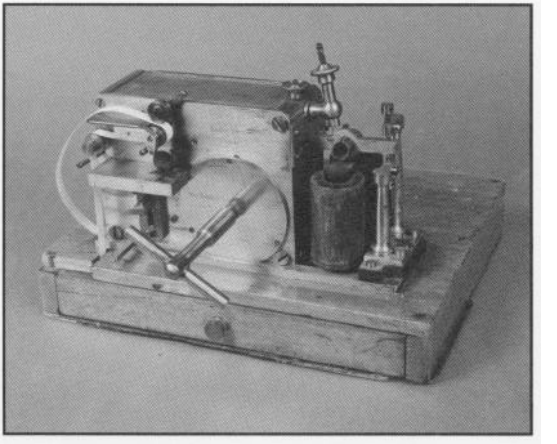


Figure 28. The Morse inker used with the coherer receiver to supply a permanent record of the wireless signals. Manufactured by Siemens Company, it was sold by the Marconi Wireless Company.

Source: Marconi Company Archives

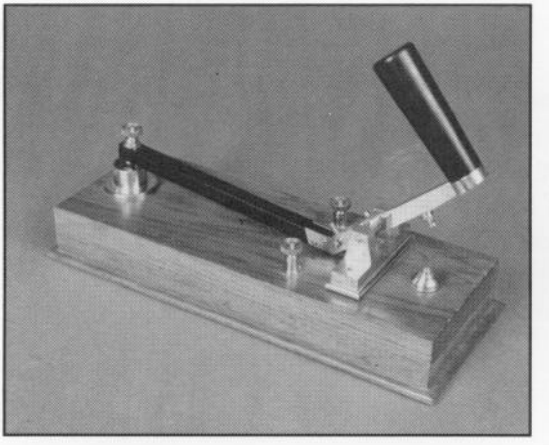


Figure 29. This is known as the "Grasshopper" key and was used in the first Marconi stations. It also served as an early form of antenna switch, for when done using the key, the arm fell back and connected the receiver with the antenna. This is a photo of a reproduction on display at the Marconi museum in Chelmsford.

Source: Marconi Company Archives

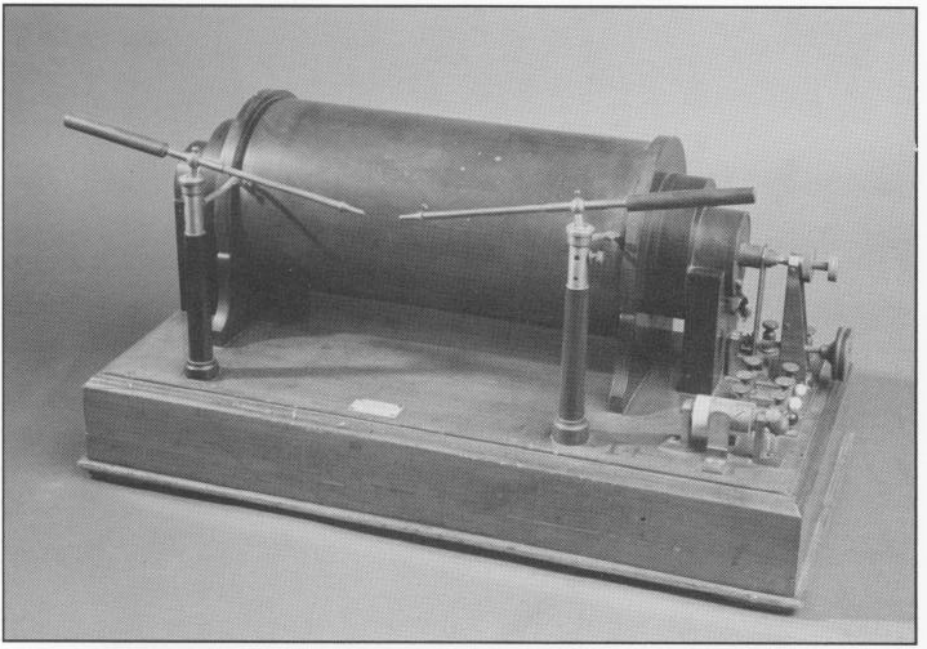
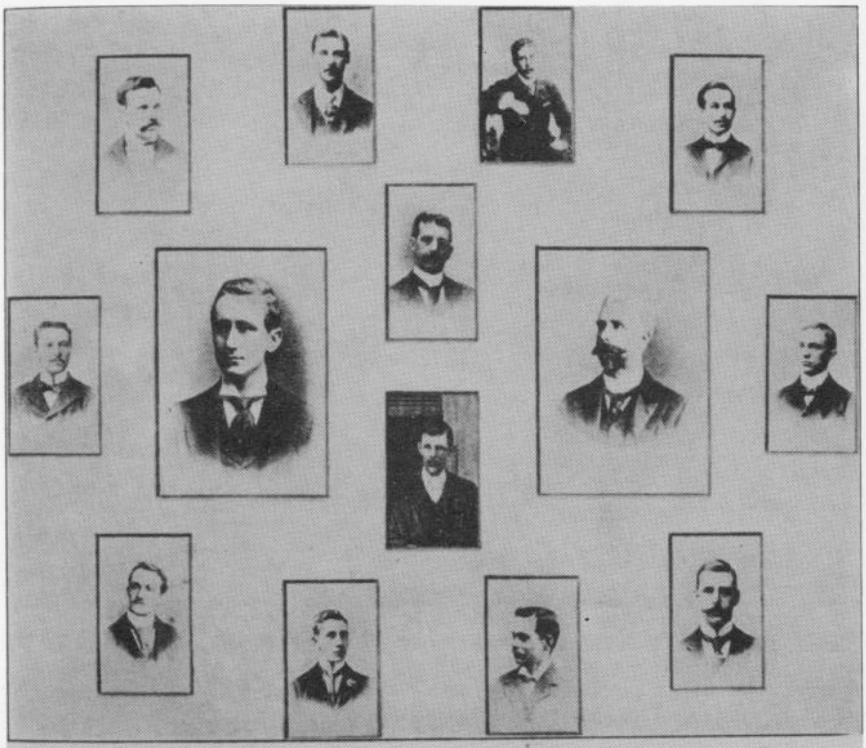


Figure 30. A 10" induction coil used in the earliest Marconi spark transmitters. The coils were wound in sections and fitted with a well-balanced condenser, a specially constructed platinum point interrupter and an adjustable spark gap. Source: Kreuzer Collection

Figure 31. Women assembling various sections of the 10" induction coil at the Chelmsford Works. The forms for pouring the insulating wax can be seen in the background. Source: Marconi Company Archives



STAFF OF THE WIRELESS TELEGRAPH AND SIGNAL COMPANY, LTD., IN 1898.

Large portrait (left), Mr. (now Senatore) Marconi; large portrait (right), Col. H. Jameson Davis (first Managing Director); top row (left to right), Messrs. T. Bowden, A. A. Cahen, Dr. Erskine-Murray, Mr. Elliott; extreme left, Mr. G. L. Bullocke; extreme right, Mr. W. W. Bradfield; in centre (top), Mr. G. S. Kemp, (below) Mr. Glanville; bottom row (left to right), Messrs. H. W. Allen, C. E. Rickard, J. Cave, P. W. Paget.

Figure 32. Staff of The Wireless Telegraph and Signal Company, Ltd. in 1898
Source: *The Wireless World*, November 1915

wireless apparatus for installation on British warships and at Admiralty land stations. The contract included spares, with an extra induction coil and an extra receiver for each installation. Deliveries began in September and were completed by November.

The Directors' Report dated December, 1900, made a short reference to the factory: "The works at Chelmsford have been improved and the plant and machinery increased, so that they can turn out all the apparatus likely to be required during the next twelve months..."

In the process of developing long distance wireless communications, many new forms of apparatus evolved. Among these, one of the most important

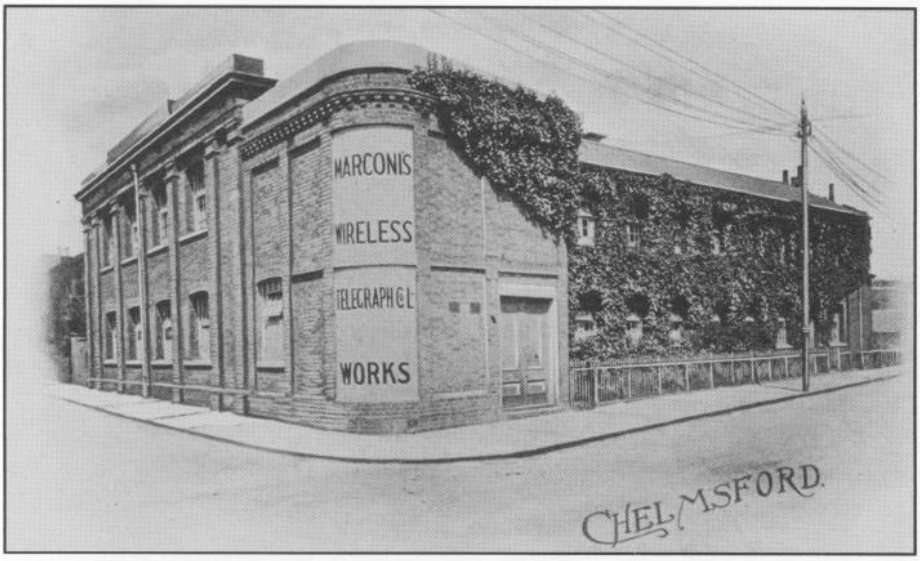


Figure 33. The Chelmsford Works as it appeared in 1900. The building is still standing, but the Marconi sign is gone.

Source: Marconi Stock Prospectus, 1903 - Kreuzer Collection

Figure 34. The mounting shop of the Chelmsford Factory, located on the 2nd floor, where the final assembly of transmitters and receivers took place.

Source: *The Marconigraph*, August 1912

Figure 35. The instrument test room at the Marconi Works in Chelmsford. Note the spacious work area available and the clean working conditions. (I wonder what's hidden in those cabinets?)

Source: *The Marconigraph*, November 1912

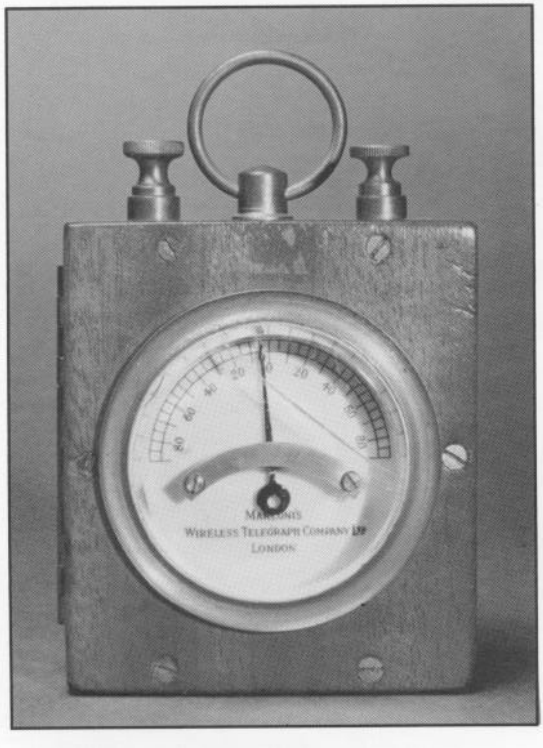


Figure 36. A galvanometer used in testing the circuits of early wireless installations, circa 1901.

Source: Kreuzer Collection

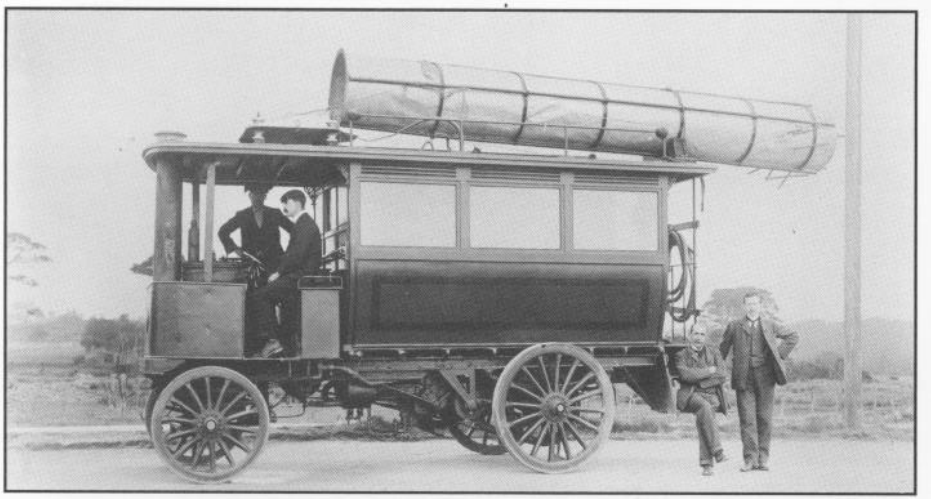


Figure 37. The first application of the Marconi system on the road. This steam motorbus includes a light zinc cylinder serving as its antenna. When stationary, the antenna was mounted vertically. Marconi can be seen standing at the rear, with John Ambrose Fleming sitting on the step. Communications were successful up to twenty miles using this outfit in 1901.

Source: Marconi Company Archives

was the magnetic detector. (Also see Fig. 112) Its development soon led to the demise of the unreliable coherer. The coherer's speed under the best of conditions was no better than ten words a minute, whereas the "Maggie" was able to match those obtained by wire telegraphy. On January 13, 1902, not long after the transatlantic test, while in New York, Marconi disclosed his idea for the magnetic detector to W.W. Bradfield. Having made a preliminary sketch in his notebook, he completed construction of the original prototype on April 20, performing his initial experiments on April 23, 1902. His first disclosure to the public was on June 12 at a meeting of the Royal Society, and he described the device in a paper released the following day.[63]

On May 3, 1902, Marconi filed his first patent for the magnetic detector. In July, he conducted the original long distance tests aboard the Italian Navy cruiser, the *Carlo Alberto*. While sailing to the port city of Kronstadt, Russia, signals were satisfactorily received on the ship from some 1600 miles away. Marconi and his party continued on to the Mediterranean, then on to Nova Scotia where signals from the Poldhu station were received. Over the years to come, the magnetic detector was to prove invaluable for the reception of wireless signals. It remained in service up to the 1920s.[64]

In 1904, the disc variable condenser was developed in Russia by C.S. Franklin while working on wireless communication during the Russo-Japanese

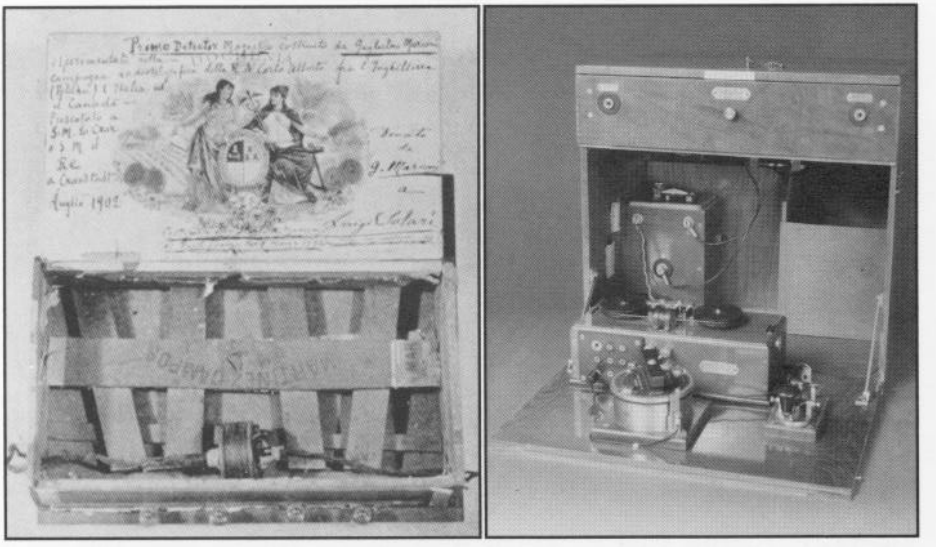


Figure 38. A prototype of Marconi's magnetic detector, used aboard the Italian Navy ship *Carol Alberto* in 1902. It was constructed in an ordinary cigar box.
Source: Luigi Solari, Marconi, 1940

Figure 39. An early transmitter-receiver designed for portable use in the field. Note the early variable condenser and miniature magnetic detector, circa 1908.
Source: Marconi Company Archives

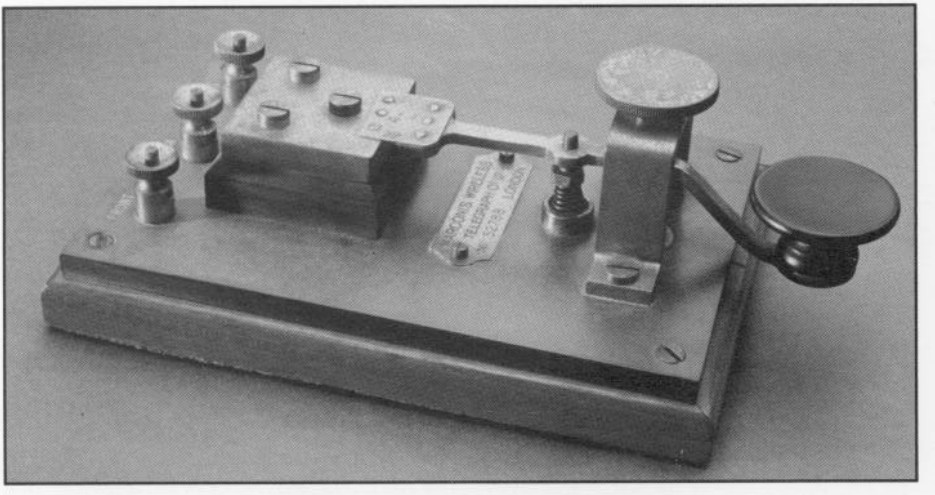


Figure 40. An unusual Marconi spark key with provisions for either normally open or normally closed contacts, circa 1907.
Source: Kreuzer Collection

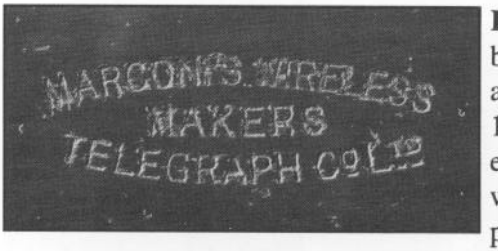


Figure 41. The earliest company label used, it was pressed into wood, and appears on apparatus built from 1900 to 1904. We've never seen an example of wireless gear identified with the name of Marconi's first company, The Wireless Telegraph and Signal Company.

Source: Kreuzer Collection

Figure 42. An ivory nameplate used from about 1903 to 1907, usually found with serial numbers in the two and three digit range.

Source: Kreuzer Collection

Figure 43. Made of sturdy brass, this nameplate can be found on apparatus built from about 1906 right up into the 1920s, with the serial numbers ranging from four to six digits.

Source: Kreuzer Collection

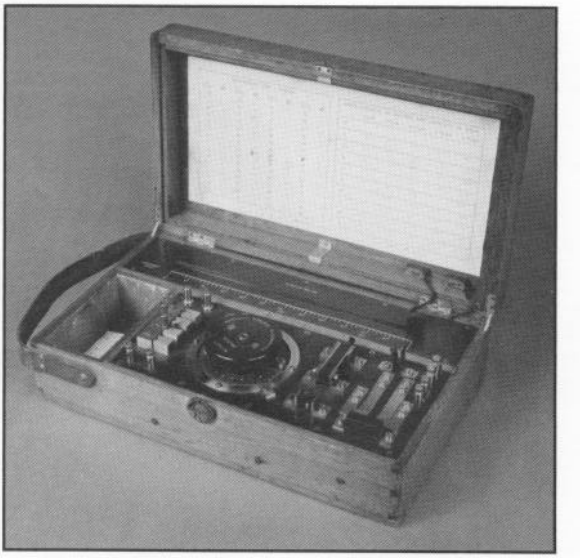
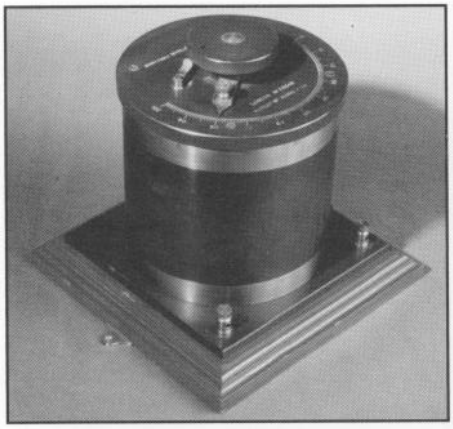


Figure 44. This instrument is known as a decremeter and dates from 1909. It was designed to measure the damping of high frequency circuits by means of simple adjustments. It could also be used for plotting tuning curves, and measuring wavelengths, capacity and inductance.

Source: Marconi Company Archives



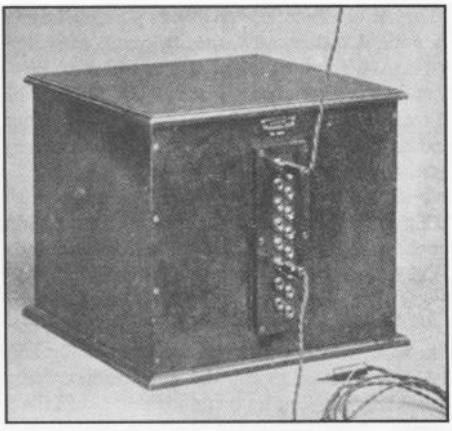


Figure 45. A large variable condenser used in laboratories where high values of capacitance were needed. Patented in 1906, the dielectric was made of ebonite. It weighs 35 pounds! Source: Kreuzer Collection

Figure 46. This box contains a tapped coil used for tuning a receiver. Known as "The 60 foot tuning inductance," it was manufactured in 1904. It predates the Multiple Tuner. Source: *Wireless World*, April 1917

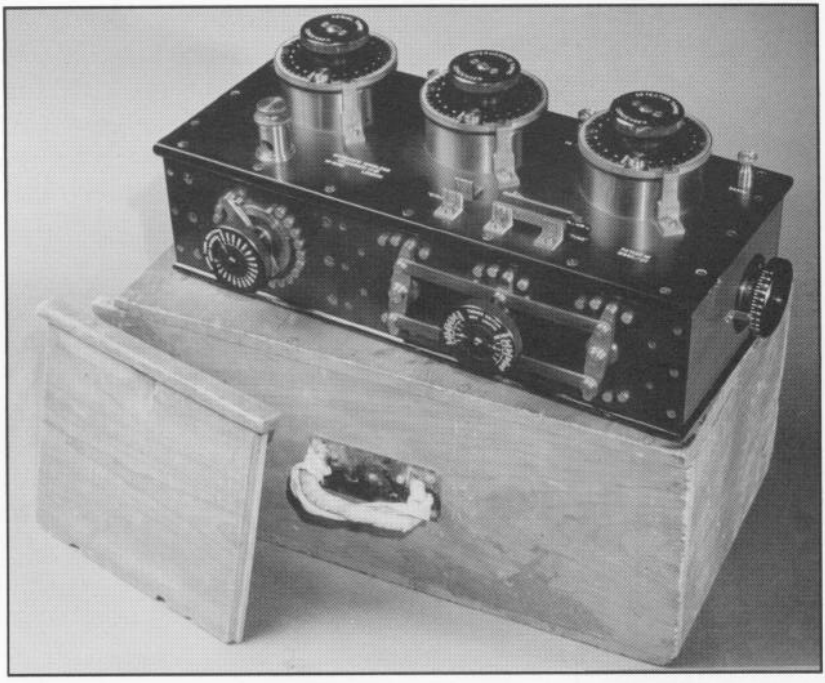
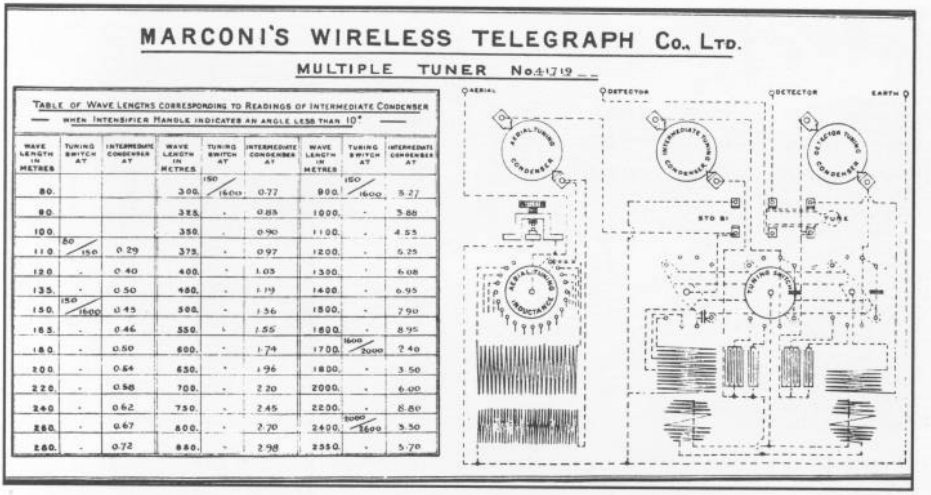


Figure 47. Marconi Multiple Tuner, patented in 1907, with the original velvet-lined shipping case. This instrument was used in the receiving circuit. Incorporating three adjustable L-C connected circuits, it was the first serious tuner ever developed. Source: Kreuzer Collection



MARCONI'S WIRELESS TELEGRAPH Co. LTD.

MULTIPLE TUNER No.4719

TABLE OF WAVE LENGTHS CORRESPONDING TO READINGS OF INTERMEDIATE CONDENSER — WHEN INTENSIFIER HANDLE INDICATES AN ANGLE LESS THAN 10°

WAVE LENGTH IN METRES	TUNING SWITCH AT	INTERMEDIATE CONDENSER AT	WAVE LENGTH IN METRES	TUNING SWITCH AT	INTERMEDIATE CONDENSER AT	WAVE LENGTH IN METRES	TUNING SWITCH AT	INTERMEDIATE CONDENSER AT
80.			300.	150/1600	0.77	900.	150/1600	3.27
90			325.	"	0.85	1000.	"	3.88
100.			350.	"	0.90	1100.	"	4.55
110.	50/150	0.29	375.	"	0.97	1200.	"	5.25
120.	"	0.40	400.	"	1.03	1300.	"	6.08
135.	"	0.50	450.	"	1.19	1400.	"	6.95
150.	150/1600	0.45	500.	"	1.36	1500.	"	7.90
165.	"	0.46	550.	"	1.55	1600.	"	8.95
180.	"	0.50	600.	"	1.74	1700.	1600/2000	2.40
200.	"	0.54	650.	"	1.96	1800.	"	3.50
220.	"	0.58	700.	"	2.20	2000.	"	6.00
240.	"	0.62	750.	"	2.45	2200.	"	8.80
260.	"	0.67	800.	"	2.70	2400.	2000/1600	3.50
280.	"	0.72	850.	"	2.98	2550.	"	5.70

AERIAL DETECTOR DETECTOR EARTH

AERIAL TUNING CONDENSER

INTERMEDIATE TUNING CONDENSER

DETECTOR TUNING CONDENSER

STD BY

AERIAL TUNING INDUCTANCE

TUNING INDUCTANCE

Figure 48. Schematic diagram of the Multiple Tuner and wave length chart as supplied from the factory. It accompanied the model illustrated in Figure 47.
Source: Kreuzer Collection

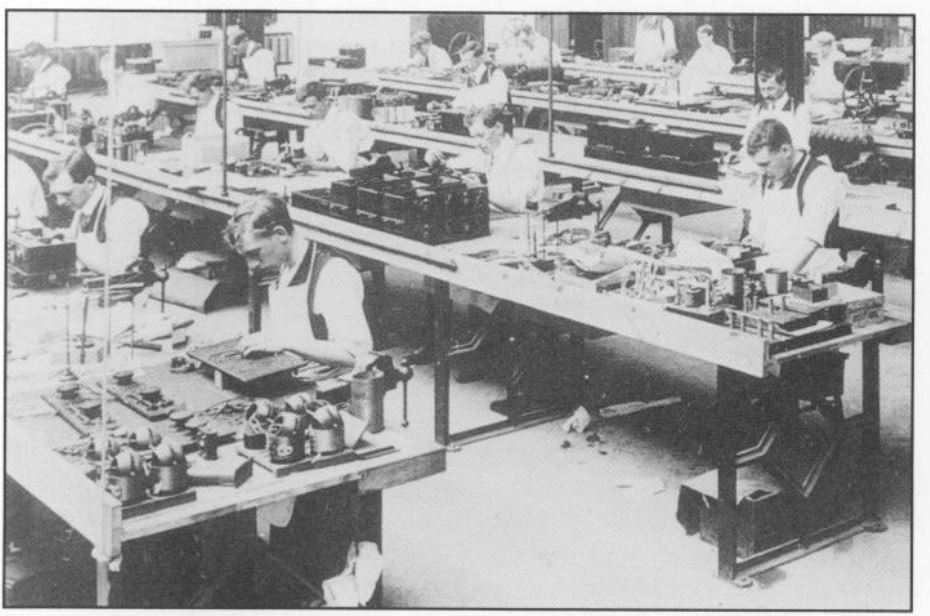


Figure 49. The assembly area at Chelmsford where the Multiple Tuners were built. Over 30 workers were employed due to the complicated assembly procedures. Source: Marconi Company Archives

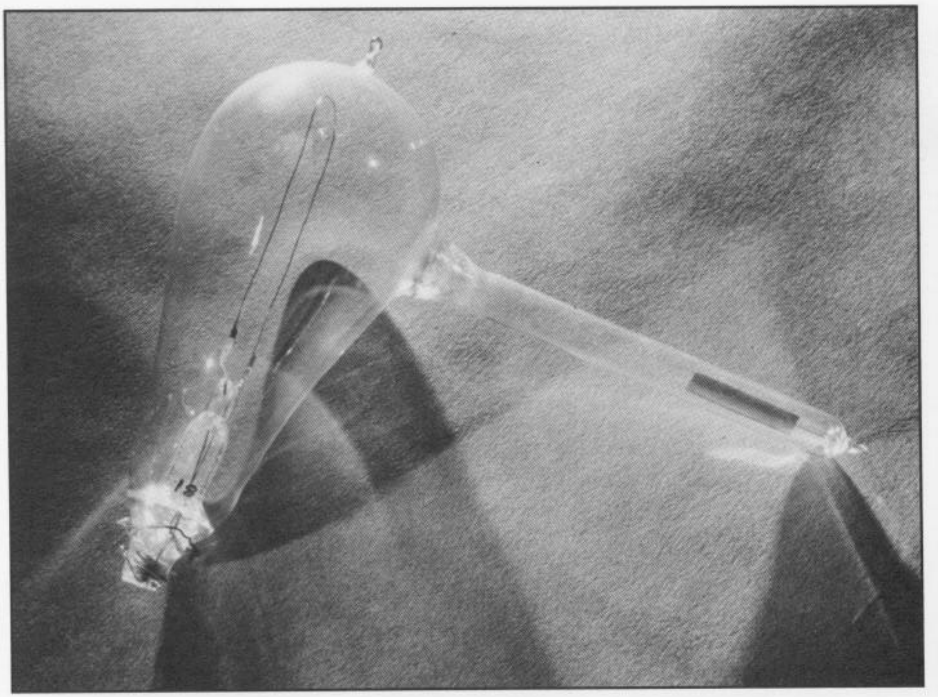


Figure 50. An 1884 Edison effect bulb, given to Sir William Preece by Thomas Edison. Note the plate at the end of the long tube on the right hand side. This diode is the grandfather of all electronic vacuum tubes.

Source: Kreuzer Collection

war. The design greatly simplified the adjustment of the receiver tuned circuit. Franklin went on to design a compact assembly of three tuned circuits, variable in wavelength and coupling. He patented this apparatus in 1907; it was known as the multiple tuner. With a tuning range of 500 to 8,000 feet, as labeled on the dial, it became a fitting companion for the famous "Maggie" or magnetic detector. Together they served to provide a true state of the art installation for shipboard and coastal stations.

One of the most important and famous of all apparatus developed at the Marconi Company was John Ambrose Fleming's diode vacuum tube. Fleming had been hired in 1899 as a technical consultant. He soon proved his value to the company by designing the first transatlantic station at Poldhu in 1901. In 1904 he began to experiment with chemical rectifiers, trying to develop a detector which would give him a visual indication of a signal. Frustrated by the absence of a breakthrough, he recalled an incident he had experienced in 1884 while working as an advisor to the Edison Electric Light Company.

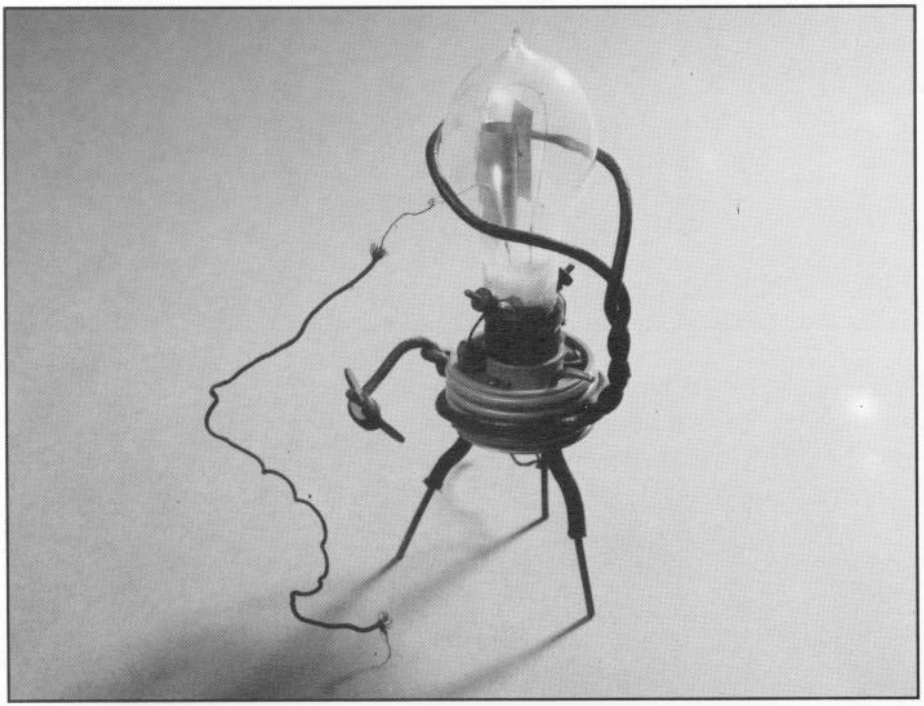


Figure 51. One of the original Fleming Valves designed and built by John Ambrose Fleming in 1904. This is the father of all electronic vacuum tubes.
Source: Marconi Company Archives

Fleming had traveled to America and visited with Thomas Edison to discuss some problems with the manufacture of light bulbs. While there Edison showed him a strange light bulb he had been working on. Edison noted a discoloration inside the glass envelope of the light bulbs due to the accumulation of carbon which had been thrown off by the filament. Hooking a galvanometer to the positive side of the D.C. supply, he discovered that a small current flowed from a piece of tinfoil placed inside the envelope. When connected to the negative side, no current flowed at all. At the time it was given the name "Edison Effect" and considered a scientific curiosity with no practical appication.[65]

Fleming decided to try this "valve" in a circuit. He connected the tinfoil plate to one side of the secondary of an oscillation coil through a galvanometer, with the opposite end hooked to the negative side of the filament's D.C. source. As he hoped, the signal was rectified by the Edison Effect bulb, providing a detector with the visual indication he had been looking for. Many experiments followed; even better results were obtained from a modern (1904) lamp constructed with a metal cylinder surrounding the

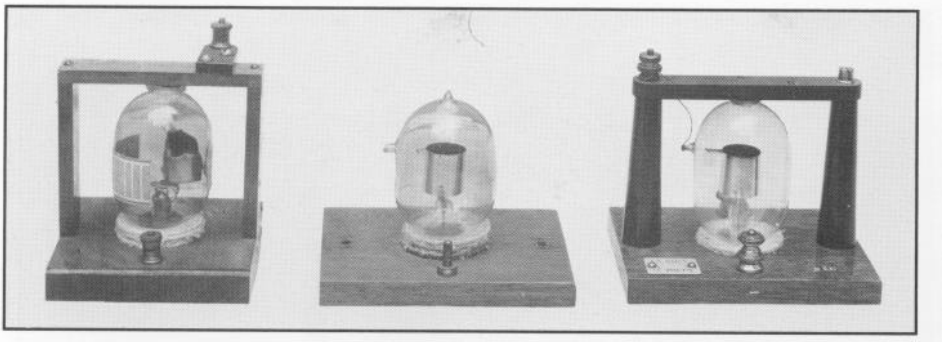


Figure 52. A group of three Fleming valves shown in various conditions. These were the first production vacuum tubes on the market. Known as "Gallows Mount" Fleming Valves, they were used as a substitute for the magnetic detector.
Source: Marconi Company Archives

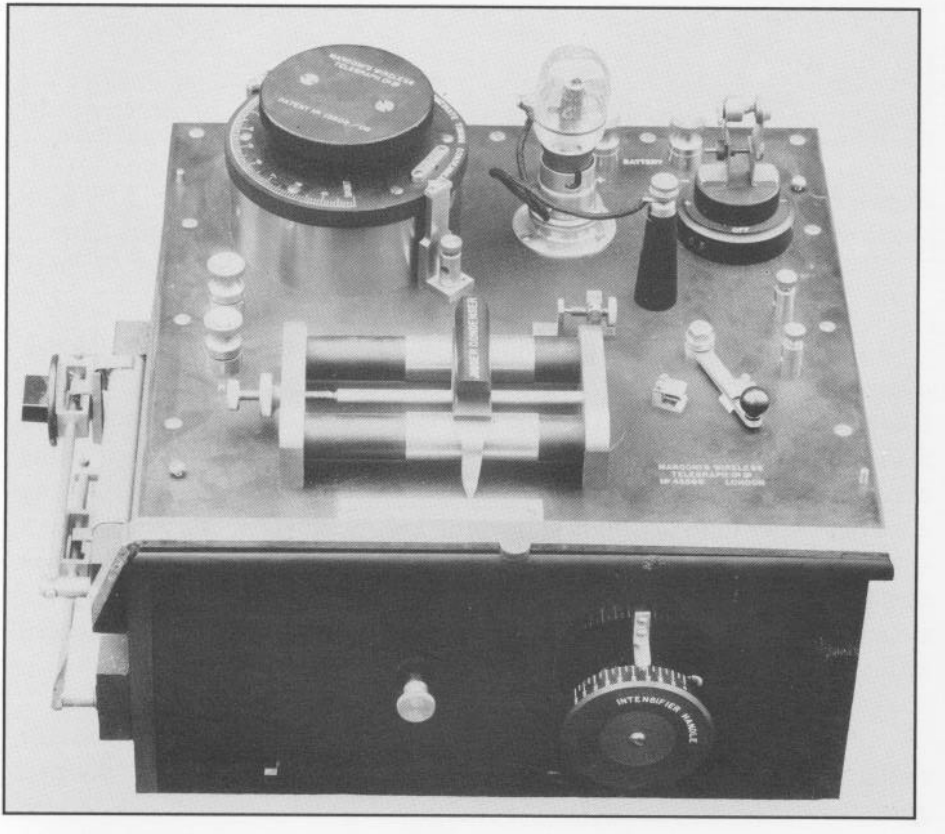


Figure 53. A Fleming Valve receiver using a crystal detector as a backup. Built around 1910, very few of these receivers are found in collections today.
Source: (Photo) Kreuzer Collection

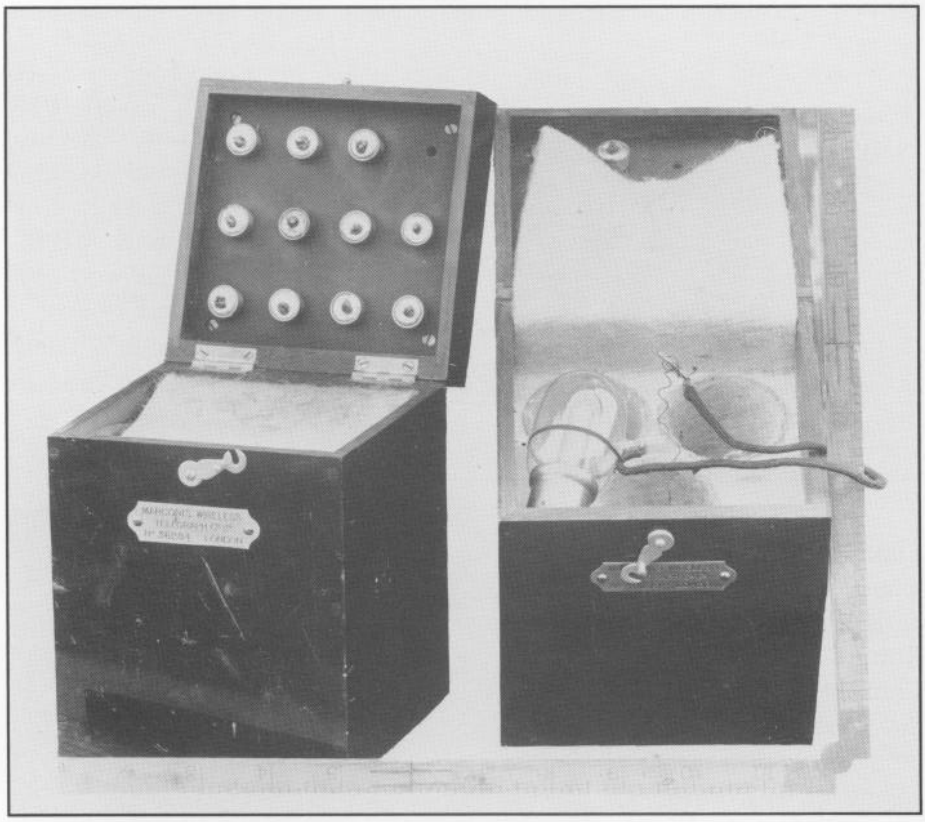


Figure 54. A spare parts kit that includes various types of crystals as well as extra Fleming Valves. These boxes would have accompanied the tuner in Figure 53. Source: Kreuzer Collection

filament. Fleming immediately applied for a patent on November 16, 1904, a date now known as the birth of the thermionic valve.

Fleming labeled it "The Oscillation Valve." Marconi recognized possibilities in the device and ordered it placed into production. Although not as sensitive or as sturdy as the Maggie, the new detector wasn't as susceptible to the effects of heavy static disturbances. For this reason the Fleming valve was often used as a standby to the magnetic detector.[66] (Also see Fig. 106.)

By December 24, 1904 the Marconi Company had 69 land stations in operation and 124 ships equipped with its system of wireless telegraphy. Both commercial and military communications benefited from the new installations. One of the main selling points which the Marconi Company presented to promising clients was the number of lives and value of equipment already saved through this important medium.[67]

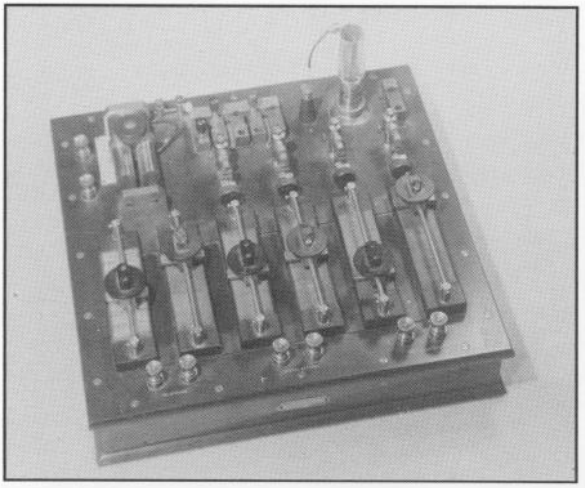


Figure 55. A British Marconi detector box, circa 1910. This unit includes provisions for switching between four different crystal detectors, as well as a Fleming Valve.

Photo: Antique Wireless Association Museum

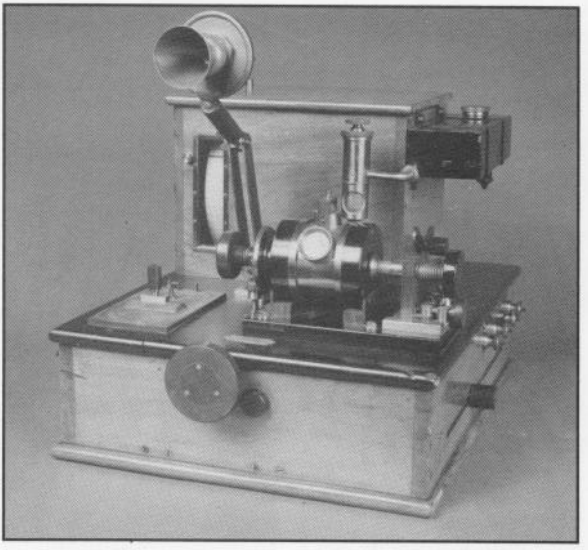


Figure 56. Marconi radiotelephone arc transmitter, designed by Captain H.J. Round of the Marconi Company in 1910. Note the visual arrangements for burning the arc in an atmosphere of hydrocarbons, along with a clockwork mechanism to rotate the anode, thereby improving the steadiness of burning.

Source: Marconi Company Archives

By early 1905 Mr. H. Cuthbert Hall, the Managing Director, decided to move the factory from Chelmsford to Dalston in North London. A large building with four floors and three wings was procured. Here wireless equipment was manufactured, as well as a new line of spark coils for the growing automobile industry. The move worked well for a time, but the strain of having two large facilities to maintain along with the construction and operation of the Glace Bay and Clifden stations depleted the company finances.

In March, 1908, with the resignation of Mr. Cuthbert Hall, Marconi took over as Managing Director of the Company. The Dalston works had become a white elephant with an unsuitable engineering department and

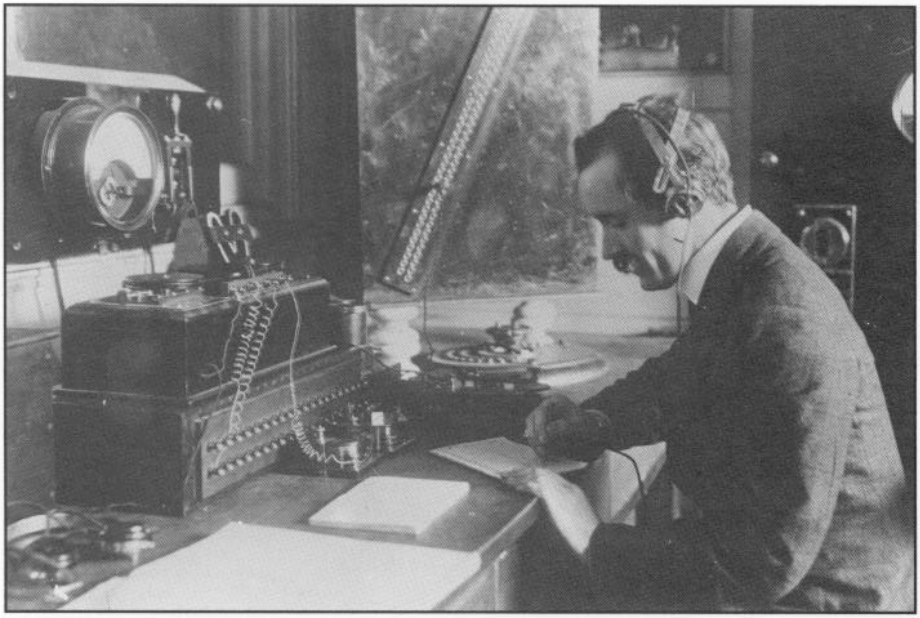


Figure 57. The receiving station at Clifden, Ireland. The magnetic detector is used with early type variable condensers and a multiple-tapped tuning coil.
Source: Marconi Company Archives

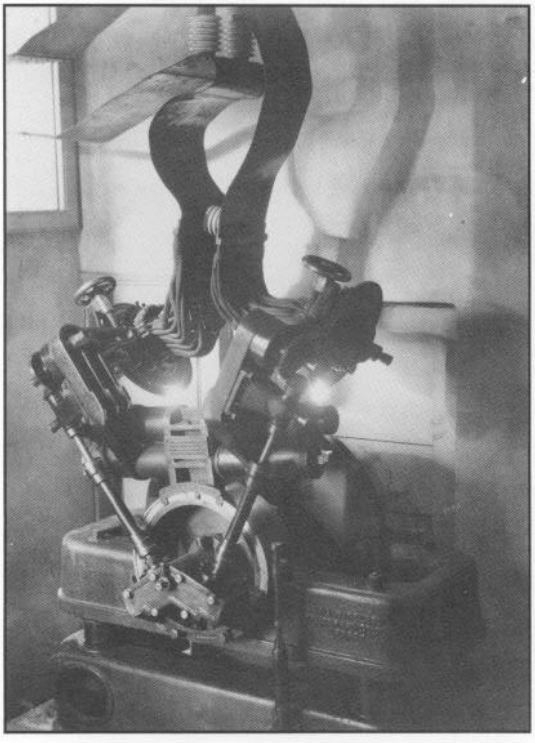


Figure 58. The rotary disc discharger transmitter in operation at the Clifden, Ireland station in 1908. Note the heavy connecting straps fed through the window.
Source: Marconi Company Archives

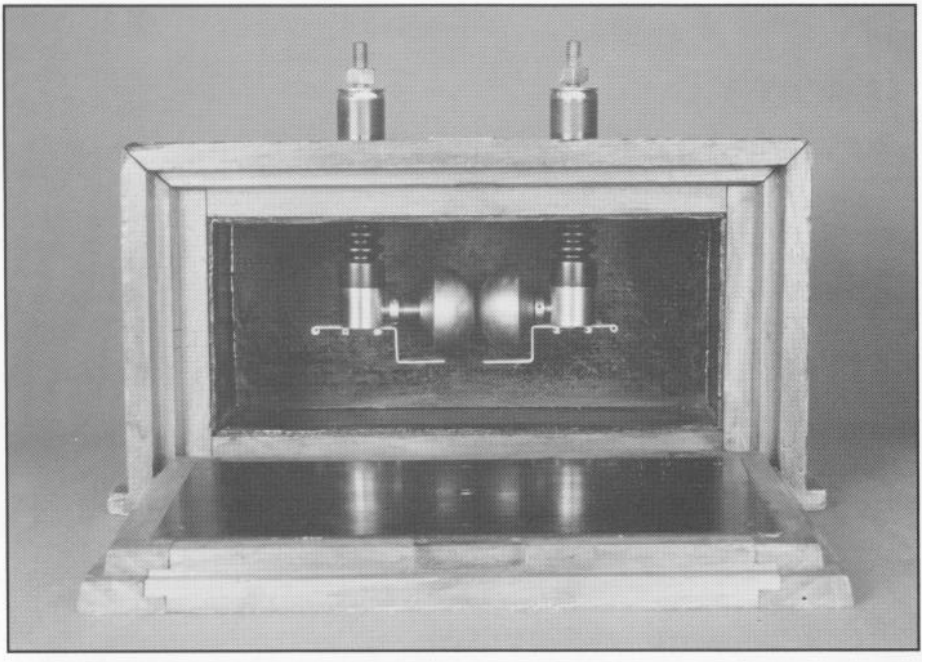


Figure 59. Enclosed spark gap used in the standard 1 1/2-kW shipboard transmitter. It consists of a pair of mushroom-shaped cast iron electrodes mounted in a 1 1/2-inch thick teak box to muffle the noise. Lime is placed in a removable zinc tray to absorb the acid produced by the spark.

Source: Marconi Company Archives

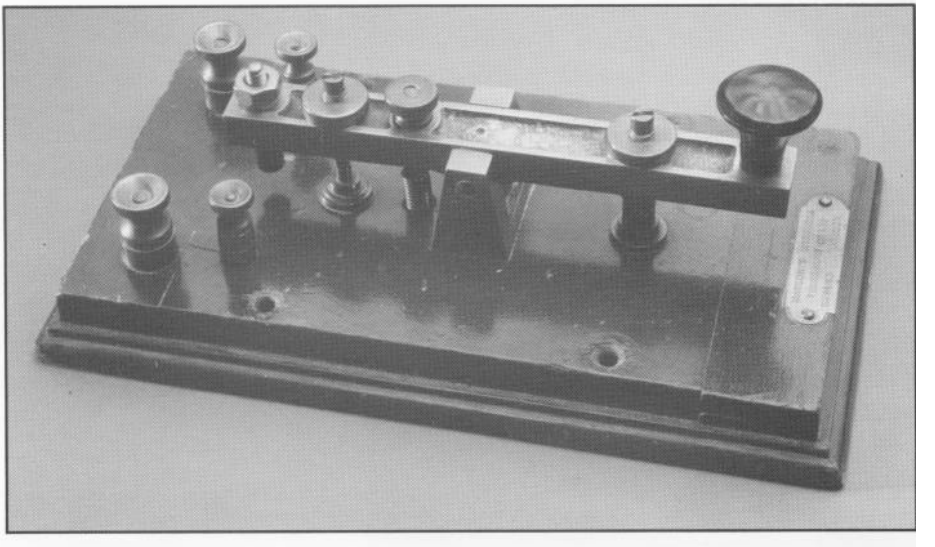


Figure 60: Marconi wireless spark key, circa 1912, used in shipboard installations.

Source: Kreuzer Collection

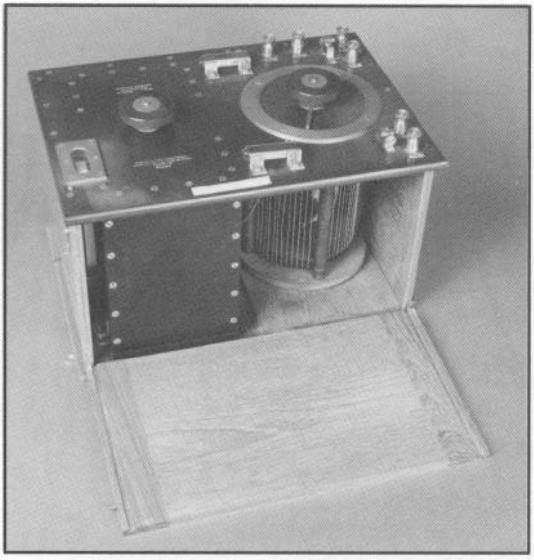


Figure 61. Marconi-Bellini-Tossi direction finder, used during World War I. This apparatus enabled the wireless operator to determine his ship's position, or the whereabouts of another wireless station.

Source: Marconi Company Archives

minimal income from the automobile ignition coil line. A decision was made to close the factory; everything was moved back to Chelmsford by mid-1908.[69]

By early 1907 Marconi was testing a new type of transmitter utilizing a high speed rotary disc, moving at 600 feet per second. It produced a regular succession of quenched sparks synchronized with an alternator which supplied the charging potential. Discharges were produced at regular intervals, giving the sparks a musical tone. It was christened the "disc discharger." By October, 1907, both the Glace Bay and Clifden stations were equipped with this new design; its output was rated at 300 kW. On October 15, 1907, with many prominent people present, the two transatlantic stations exchanged messages comprising a total of 10,000 words sent and received![70]

Another important innovation fostered by the Marconi Company was the radio direction finder. Originally developed by E. Bellini and A. Tossi in 1907, their patents were purchased by the Marconi Company in February, 1912. Dr. Bellini joined the technical staff as a consultant. The first installation of the Marconi-Bellini-Tossi direction finder was in 1912 on the steamship *Mauretania*. Two large fixed triangular loop aerials were suspended by their apices at right angles to each other. The reception of the signals was by means of a crystal receiver, which unfortunately rendered the direction finder insensitive and limited its range. Later types used valve tuners which were more selective and sensitive.[71]

Radio direction finders revolutionized both marine and aerial navigation. In World War I, they made a tremendous difference in keeping an

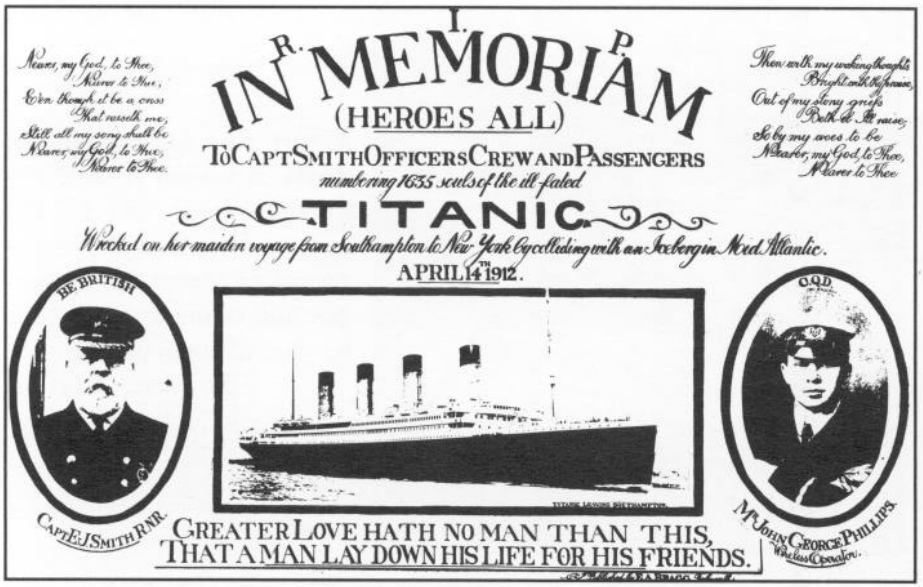

IN R.I.P. MEMORIAM
(HEROES ALL)
TO CAPT SMITH OFFICERS CREW AND PASSENGERS
numbering 1635 souls of the ill fated
TITANIC
Wrecked on her maiden voyage from Southampton to New York by colliding with an Iceberg in Mid Atlantic.
APRIL 14TH 1912.
Nearer, my God, to Thee,
Nearer to Thee,
Even though it be a cross
That raiseth me;
Still all my song shall be
Nearer, my God, to Thee,
Nearer to Thee.
Then with my waking thoughts
Bright with Thy praise,
Out of my stony griefs
Bethel I'll raise;
So by my woes to be
Nearer, my God, to Thee,
Nearer to Thee.
BE BRITISH
CAPTE.J.SMITH R.N.R.
O.Q.D.
M.JOHN GEORGE PHILLIPS
Wireless Operator.
GREATER LOVE HATH NO MAN THAN THIS,
THAT A MAN LAY DOWN HIS LIFE FOR HIS FRIENDS.

Figure 62. A memorial postcard published not long after the sinking of the *Titanic*. It shows Captain E.J. Smith and John George Phillips, the chief wireless operator. Source: Kreuzer Collection

eye on the German fleet, and, mounted in mobile trucks, they were also used on land. They recorded the movement of the Zeppelins and the changing position of the German trench stations. By 1917 a system consisting of a rotating frame direction finder was developed which enabled the British to locate wireless-equipped German aircraft as they flew over the front lines. Within one week eleven German spotting planes were brought down using the bearing information supplied.

The greatest peacetime marine disaster in history occurred on the evening of April 14, 1912, when the White Star Liner *Titanic* struck an iceberg and sank in less than three hours. Even though 712 people were saved that night through the use of wireless, 1,517 unlucky souls were lost. One hour before striking the iceberg, the *Titanic* was warned by the wireless operator on board the *Californian* that there were icebergs in the area. The *Titanic* acknowledged the report, but then rudely replied: "Shut Up I'm Busy With Cape Race"[72] (the Newfoundland shore station – see also Figure 112.)

Although the *Titanic* was within sight of the *Californian*, her wireless operator had gone to bed and even distress flares which were sighted went unheeded. The *Carpathia* responded to the *Titanic's* SOS call but was 58 miles away and didn't arrive until about 4:20 in the morning. By the time it had

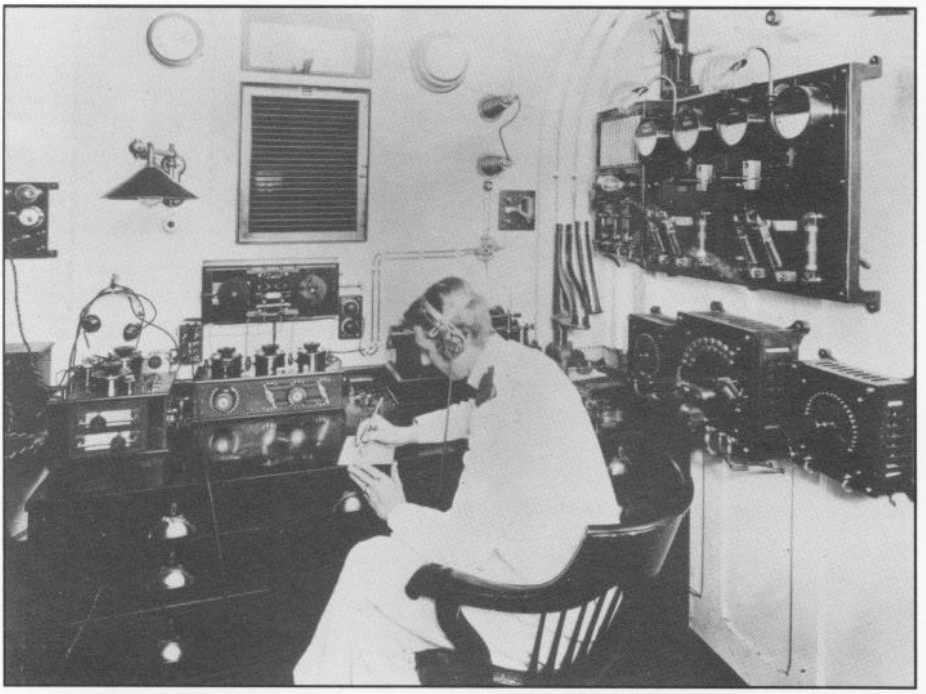


Figure 63. Wireless room of the *Olympic*, the sister ship of the *Titanic*. The apparatus included a Fleming valve receiver, as wellas the magnetic detector/ multiple tuner installation. Source: Marconi Company Archives

reached the scene and began picking up survivors from the lifeboats, two hours had passed since the sinking and many lives were lost. This incredible tragedy awakened the world to the importance of the use of wireless on shipboard.[73]

Ultimately some good did emerge from the catastrophe. Two months following, on June 4, an International Radio-Telegraphic Conference was held in London. Various representatives from the countries attending proposed important legislation relating to the regulation of wireless apparatus aboard ships. On July 5 the delegates signed the charter. The International Conference on the Safety Of Life At Sea was held on January 20, 1914. Representatives from sixteen nations signed an agreement, which contained 74 articles relating to the safety of shipping, including the use of wireless aboard ships.[74]

One of the articles proposed that all merchant ships carrying fifty or more passengers must be equipped with wireless. Certain classes of ships had to have a minimum of two wireless operators to keep a 24-hour continuous watch. Another article addressed the minimum range requirements, which were set for both the main wireless equipment and the auxilliary equipment. Also, an independent power source must be provided, capable of working at least six hours, in case of trouble with the primary source of power.

Figure 64. Souvenirs presented at the banquet given by the Marconi Company for the delegates of the June, 1912 International Radiotelegraphic Convention. Each male delegate received a sterling silver model of the disc discharger. The ladies were given a sterling silver perfume flask, engraved with the details of the convention. A dime is shown for size comparison.

Source: Kreuzer Collection

Figure 65. Early form of wavemeter incorporating an internal battery and wavelength chart, circa 1909.

Source: Kreuzer Collection

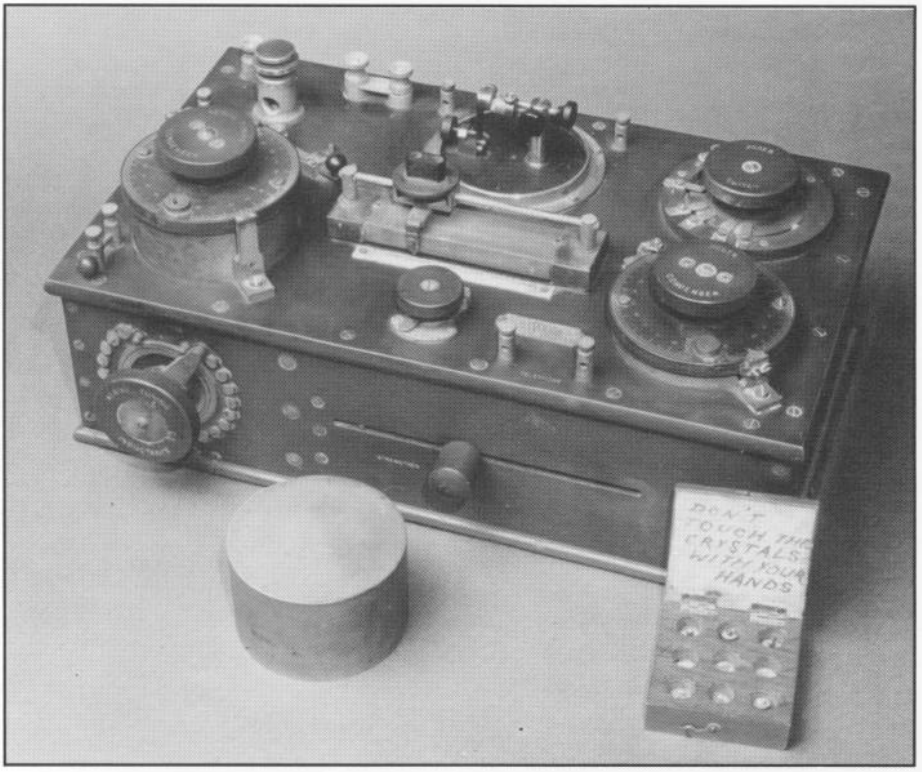


Figure 66. Marconi Universal Crystal Receiver, developed in 1912, which tuned a range of 300 to 3000 meters. This unique receiver incorporated an internal loose coupler and a crystal detector protected by a brass cover. The detector circuit is designed specially to disconnect both sides by means of internal relays when the transmitting key is depressed. This feature prevented the detector from burning out when strong currents were induced during transmission. A container of spare crystals is shown next to the set.

Source: Kreuzer Collection

Eventually the company's business completely outgrew the capacity of the Hall Street Chelmsford works. In 1911 it was decided to build a new factory at New Street on ten acres of land next to the main railway lines. The main building measured 466 feet by 150 feet deep, with excellent lighting and layout design. An extensive number of back orders had been accumulating prior to the Titanic disaster. Combined with the subsequent orders, and the impact of the long-awaited "Imperial Wireless System," which sought to connect all the British colonies by wireless, there was reason enough to complete the first radio factory in the world, built expressly for the purpose.[75]

It was with great foresight that the Marconi Company constructed the factory at New Street, for on August 4, 1914, England entered the Great War

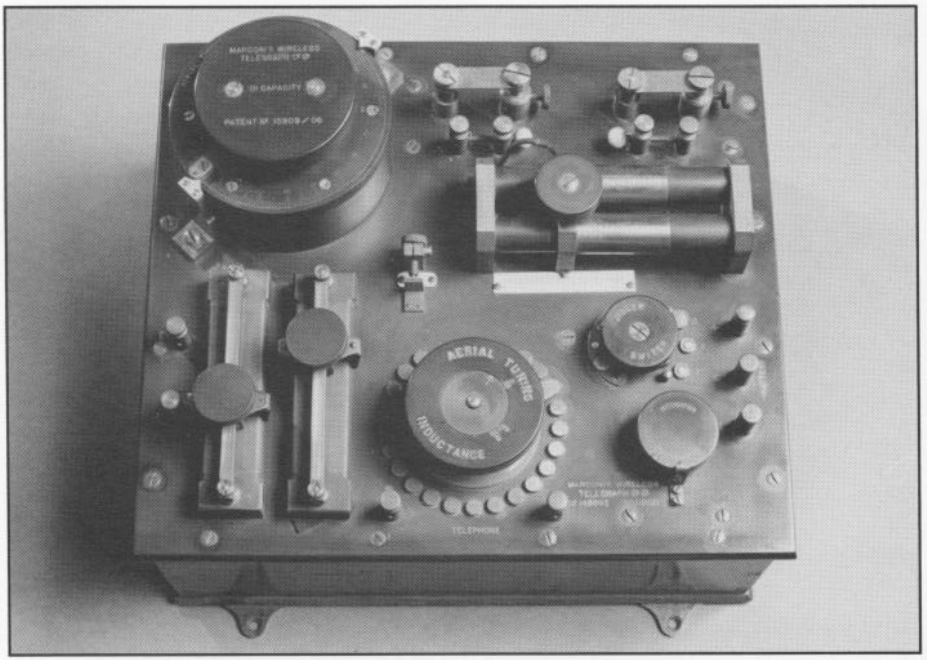


Figure 67. Type 16 Balanced Crystal Receiver, the standard receiver for the 5-KW ship and shore installations. It was designed in 1914 to tune from 250 to 3500 meters. Using two crystal detectors, this design provided the option of either working them simultaneously or independently.

Source: Kreuzer Collection

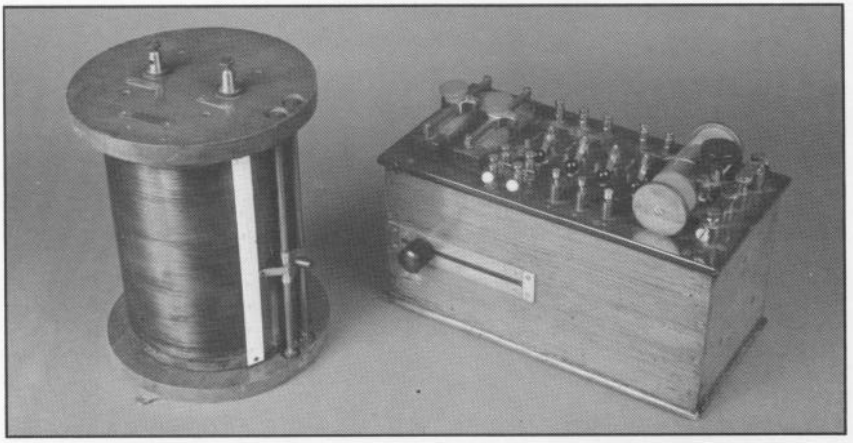


Figure 68. Marconi Type 31 shipboard receiver, covering a wavelength of 300 to 600 meters, and in use about 1916. The instrument is fitted with two crystal detectors, which may be used for independent or balanced working as desired. An advantage of the aerial tuning inductance—wavelengths of 200 to 2500 meters are possible.

Source: Marconi Company Archives

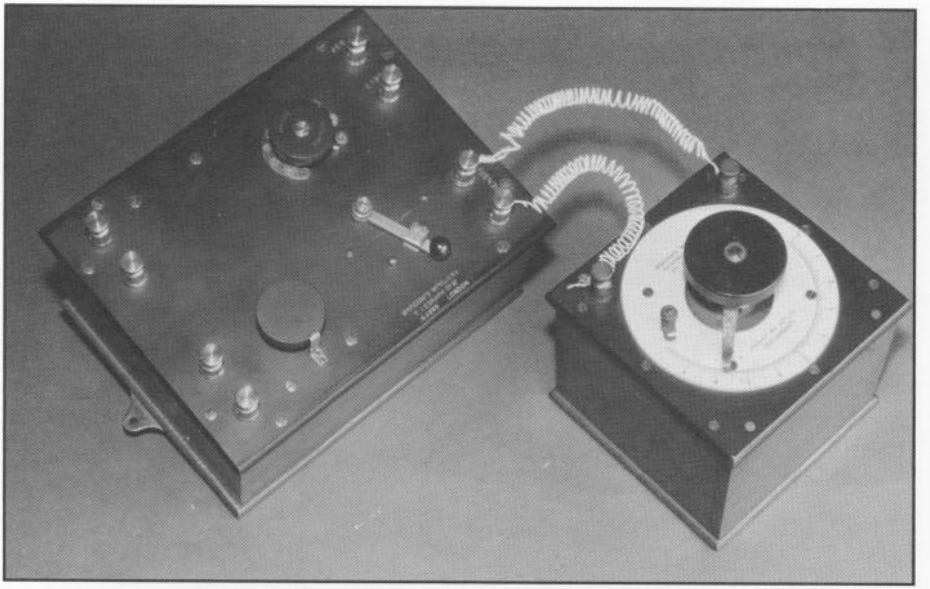


Figure 69. This tuner was designed for use by the infantry around 1917. It required the use of an external tuning condenser as well as an outboard detector unit.
Source: Kreuzer Collection

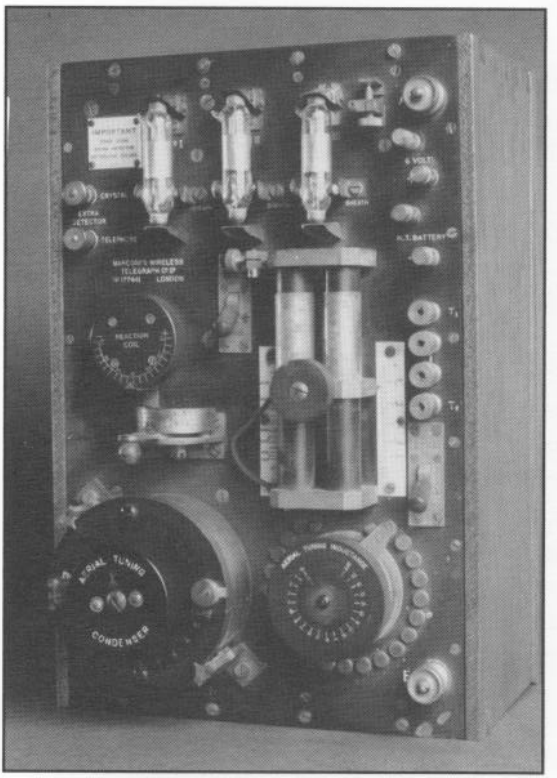


Figure 70. This unusual set is known as the Type 38 Field Station Receiver and was developed in 1917 for use in World War I. It was one of the earliest receivers to use the Type Q valve. One valve is the detector, while the other two serve as audio amplifiers. Provisions were made for an outboard crystal detector.
Source: Kreuzer Collection

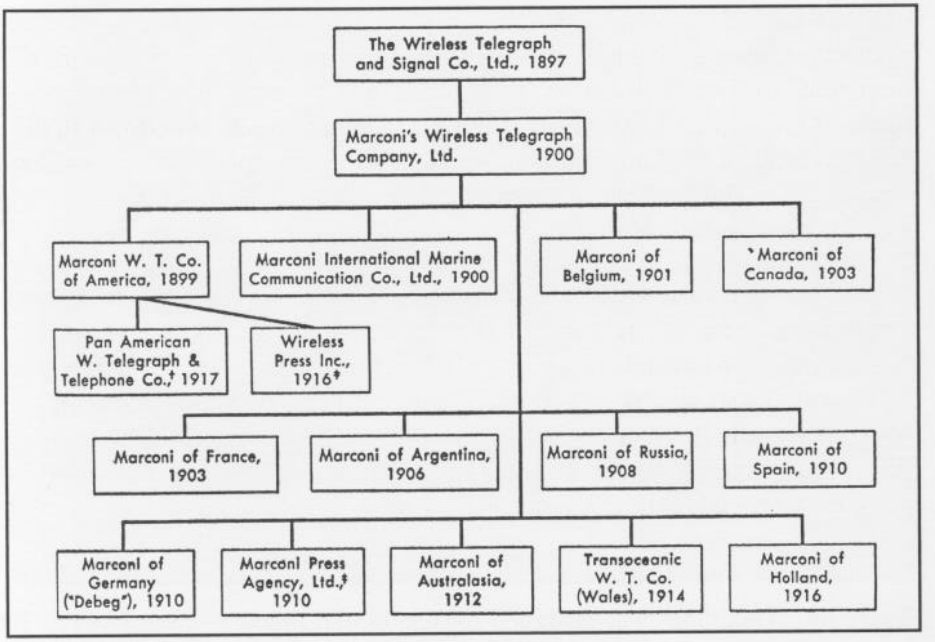

The Wireless Telegraph and Signal Co., Ltd., 1897
Marconi's Wireless Telegraph Company, Ltd. 1900
Marconi W. T. Co. of America, 1899
Marconi International Marine Communication Co., Ltd., 1900
Marconi of Belgium, 1901
Marconi of Canada, 1903
Pan American W. Telegraph & Telephone Co.,† 1917
Wireless Press Inc., 1916†
Marconi of France, 1903
Marconi of Argentina, 1906
Marconi of Russia, 1908
Marconi of Spain, 1910
Marconi of Germany ("Debeg"), 1910
Marconi Press Agency, Ltd.,‡ 1910
Marconi of Australasia, 1912
Transoceanic W. T. Co. (Wales), 1914
Marconi of Holland, 1916

Figure 71. A chart of the principal Marconi companies from 1897 to 1917. Source: W. Rupert Maclaurin, *Invention & Innovation In The Radio Industry*, 1943, p. 43

against Germany. Immediately the output of the Chelmsford works was directed towards the war effort. Many new types of apparatus were developed during the war, and perfected as a result of their use in the field.

THE MARCONI WIRELESS TELEGRAPH COMPANY OF AMERICA

THE ALDENE, N.J., FACTORY

It wasn't until 1912 that manufacturing facilities were finally acquired by the Marconi Company in the U.S. Previously the main purpose of the American company had been to conduct a wireless telegraph service specifically with ships along the east coast. By 1901 a few German and English transatlantic liners were equipped with wireless apparatus, making it necessary to build stations along the coast. Initially, only the Nantucket and the Babylon Long Island stations were erected. They carried on a fine business transmitting messages from passengers when ships were near shore, or with the various Marconi stations located along the transatlantic run.[76]

The first Chief Engineer of the American company was W.W. Bradfield, succeeded by Frederick Sammis in 1908. By 1904 J.J. Brennan had

come to the Marconi New York shop as a machinist, and continued as head of the machine shop after the RCA merger. He personally built many items of equipment for Henry Round while a technician, as well as made-to-order apparatus for Marconi. Although the original intention was to perform all the manufacturing in England, the high import duty on complete sets persuaded them to ship finished but unassembled parts duty free, or nearly so, and assemble them in New York.[77]

> They needed a small New York shop to make occasional repairs to equipment on the ships and also make repairs to land stations, as well as a storeroom for parts and equipment. The Front Street attic shop and later 37 Water Street served this purpose and occasionally when Guglielmo Marconi was in this country he wanted special apparatus made, for he was continually experimenting and developing new ideas. The New York shop also built special parts for South Wellfleet for tests.[78]

These shops had a small lathe and assembly benches but were essentially used for repair.

Most metal parts were imported from Chelmsford, England, using standard English Marconi style apparatus. Wood work was performed by Bubek and Guerin on 18th Street, while special metal work and castings were done by the Manufacturers and Inventors Electric Company on Gold Street near the Marconi shop. Transformer cases, square forms for early oscillation transformers, and later loading coil forms were made a few at a time in the cabinet shop and assembled at the Marconi shop.

As of 1905 there were six or eight people in the New York office, and two in the shop. With the operators at the four coast stations, there was a total of about 25 employees in New York.[79]

> Up until about 1910 American Marconi was a very small company, operated very economically. Some American operators used to call it 'That Cheap Dago Push Cart Wireless Company.' True, some of the shops including Seattle did have ordinary vegetable peddlers' push carts for emergency use to take parts to a ship in a hurry, and once I was glad of it when a ship about ready to sail developed trouble and I had to rush a new 10-inch induction coil several blocks down the waterfront in a hurry. Then I also heard that A.P. Gianini, founder of the Bank of America, carried a million dollars in a vegetable pushcart during the emergency following the San Francisco earthquake and fire, so the things can be very useful.[80]

American Marconi's chief competitor in the wireless business was the United Wireless Company. They had been infringing on Marconi's inductive

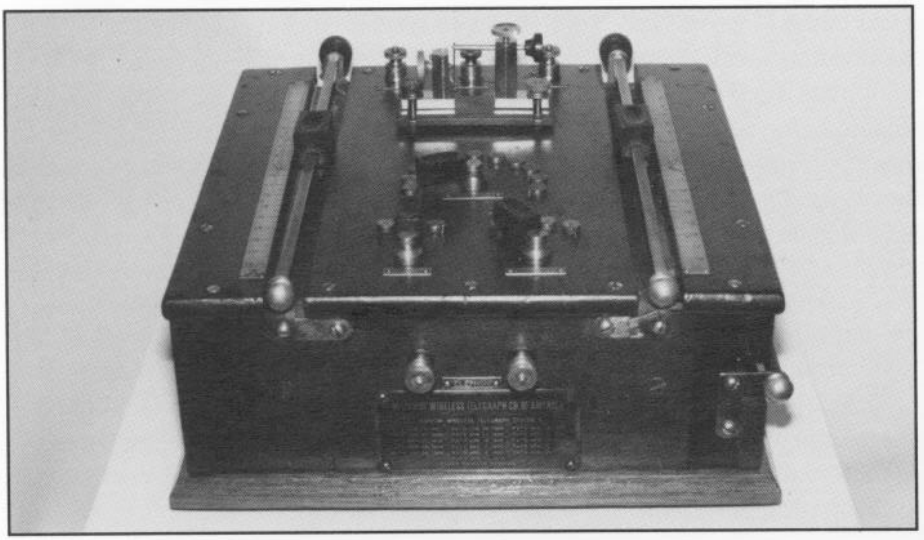


Figure 72. An updated United Wireless Type "D" tuner, with minor circuit changes and the addition of a Marconi Wireless Telegraph Company nameplate. Source: Barry Janov Collection

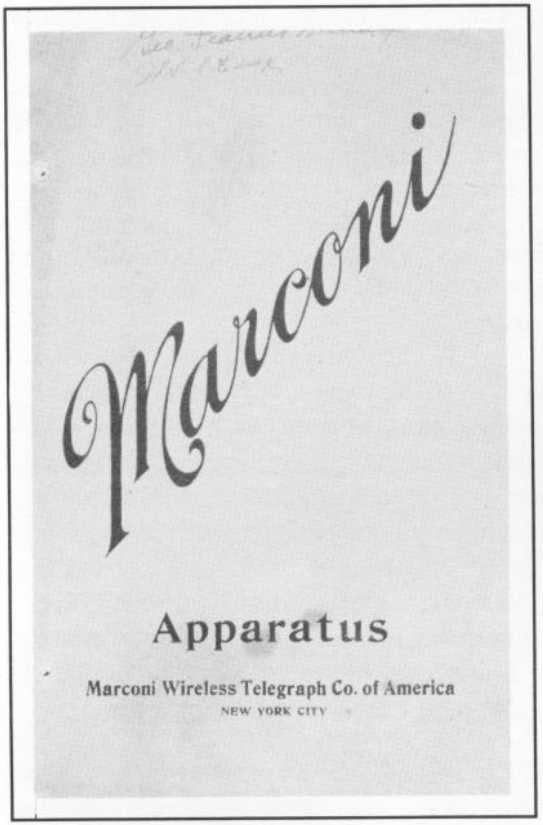
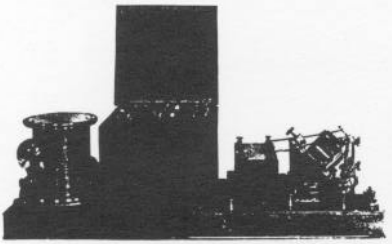


Figure 73. Probably the first American Marconi catalog, circa 1912, published before the Aldene plant was in full swing. Source: Kreuzer Collection

COHERER SETS.



These are the Marconi commercial coherer sets which but a few years ago were in general use at ship and shore stations.

They consist of the original finely finished Marconi coherer, decoherer, air tight polarized relay, jigger and batteries mounted upon a mahogany base with binding posts for connecting to the antennae and ground and to a sounder, Morse inker, bell or other device whose operation it is desired to control by Hertzian waves.

Having a considerable stock of these admirable receivers and having discontinued their commercial use we have located the price at practical cost.

This instrument occupies a space 23 in. x 8 in. x 8 in.

Complete with one coherer and iron screening case.

Price, $95.00 Extra Coherer, $5.00.

KEY.

This key is small, neat, light in operation and with the knob close to the table. The base is of fireproof material and metal parts of lacquered brass. We have designed it to provide an inexpensive desirable key for the experimenter.

15 ampere	A. C.	Price.....	$5.00
30 "	A. C.	"	5.75
15 "	D. C.	" with condenser in case.	6.50
30 "	D. C.	" with condenser in case.	7.25

Figure 74. A page from the 1912 Marconi catalog showing a complete coherer receiver available for only $95.00

Source: Kreuzer Collection

MAGNETIC DETECTOR.

As with the greater part of the apparatus listed in this catalog we have tried in this magnetic detector to embody all the features of the Marconi commercial apparatus that are necessary for the experimenters purpose and at the same time make a low priced instrument.

As the imported driving mechanism of a commercial instrument is necessarily expensive we have designed this detector to be driven by hand. In other respects this instrument embodies all the good qualities for which the commercial magnetic detector is justly famous.

It is the most durable wireless detector made, not damaged by static, vibration, dust, moisture, induction or kick back from transmitter. Can be used in shunt around small gap in break system. Requires no adjustment, no battery, and only 160 ohm telephones.

Price, $10.00. Extra Bands, $1.50 each.

With spring motor drive. Price, $19.50.

THE FLEMING OSCILLATION VALVE.

This is the type of detector with which the Marconi Transatlantic reception is accomplished. Operates on four to six dry cells.

Detector complete with base. Price, $3.50 each. Extra Valves, $2.50 each. Add 10c. for postage.

TUBULAR VARIABLE CONDENSER.

This neat little instrument has a remarkably wide capacity range considering its small cost and where a less expensive instrument than the Marconi disc condenser is sought, is highly desirable for use in connection with the secondary circuit of the inductive tuner and in similar circuits.

It has a graduated scale.

Price, $3.00.

Figure 75. Another page from the Marconi catalog showing a very unusual magnetic detector, complete with spring motor drive, for only $19.50. Also listed is a Fleming valve for $3.50.

Source: Kreuzer Collection

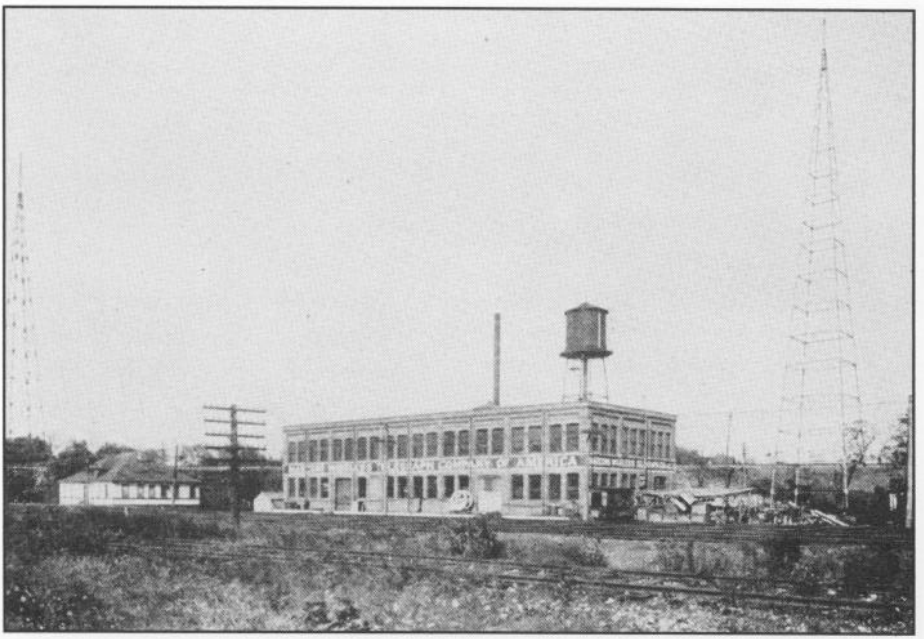


Figure 76. The Marconi plant at Aldene, New Jersey as it looked in its first year, 1913. Two additions to the plant were to follow; the first in 1917, and the last in 1918, to keep pace with the demand during wartime.

Source: 1918 Marconi Company Annual Report

coupling patent, #7777, for some time, so eventually he filed suit against them, in 1911. A notice in *Modern Electrics* on page 27 of the April, 1912, issue disclosed the following information:

> As a result of a merger which has been brought about between the Marconi Wireless Telegraph Company and the United Wireless Telegraph Company, when the suit of the former against the latter corporation for alleged infringement of patent rights came up in the United States District Court on March 25th, the United Wireless entered no defense and consented to the granting of a decree in favor of the Marconi Company.
>
> As a further result of the merger all the stations and contracts of the United Wireless will be taken over by the Marconi Company. This involves about 500 ship and 70 land stations in the United States.
>
> The absorption of the assets of this company gave the American Marconi Company a practical monopoly of the supply of apparatus and operators for radio communication in the United States.[81]

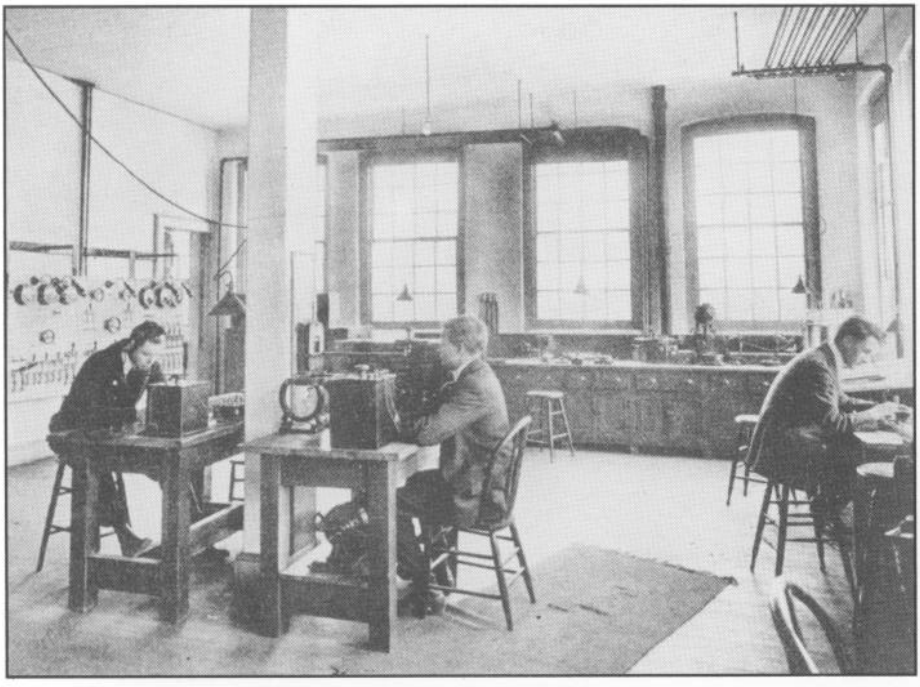


Figure 77. The research laboratory at Aldene, operated under the guidance of Marconi's research engineer, where the original investigations were made and new apparatus evolved. Source: *Wireless Age*, February 1914

This relief from a powerful source of competition added to the business prestige of the American company, thereby providing control over about 90% of the American ship-to-shore business. Marconi also procured the engineering department from United, including Harry Shoemaker, who became Chief Development Engineer in charge of making immediate design changes.

In 1912, with a great increase in business and orders pouring in, the management decided it was time to build a larger production facility.

The company acquired land, built and equipped a 20,000 square foot factory in Aldene, New Jersey, near Roselle Park, for producing wireless equipment for its own needs and for sale.

The building was "L" shaped with the testing department, transformer room, plating room, stock rooms and the power plant located on the first floor. The second floor incorporated the machine shop, research laboratory, tool rooms and the factory offices.[82]

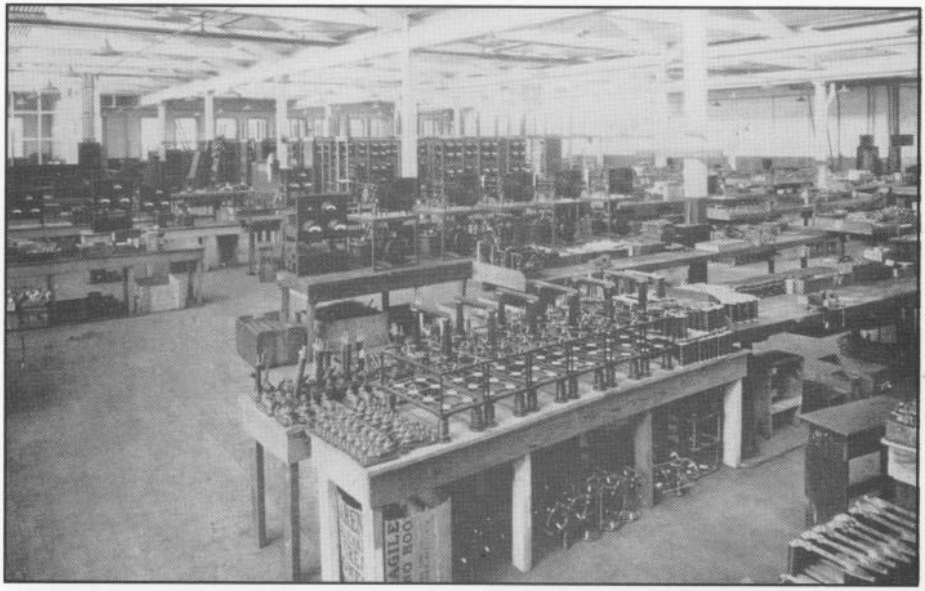


Figure 78. The assembling and test department of the American Marconi factory at Aldene, New Jersey Source: *Manual Of The Marconi Institute*

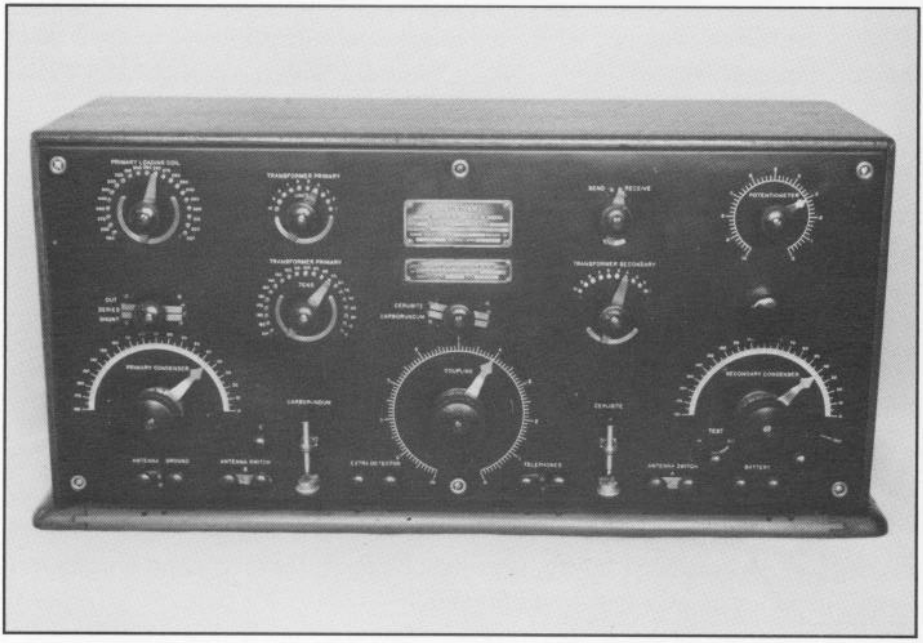


Figure 79. A very impressive receiver, this is the Marconi Type 101. It tunes from 200 to 7500 meters, and is the first receiver designed and made in its entirety at the American Marconi plant in Aldene.

Source: Richard Groshong Collection

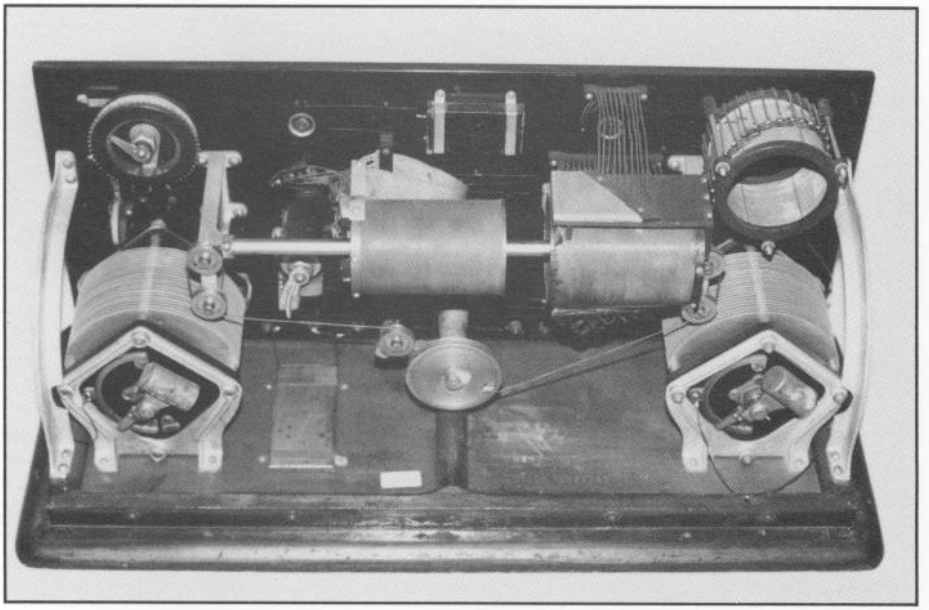


Figure 80. An internal view of the Type 101 receiver showing the large internal loose coupler which is operated by a system of pulleys and cable.
Source Richard Groshong Collection

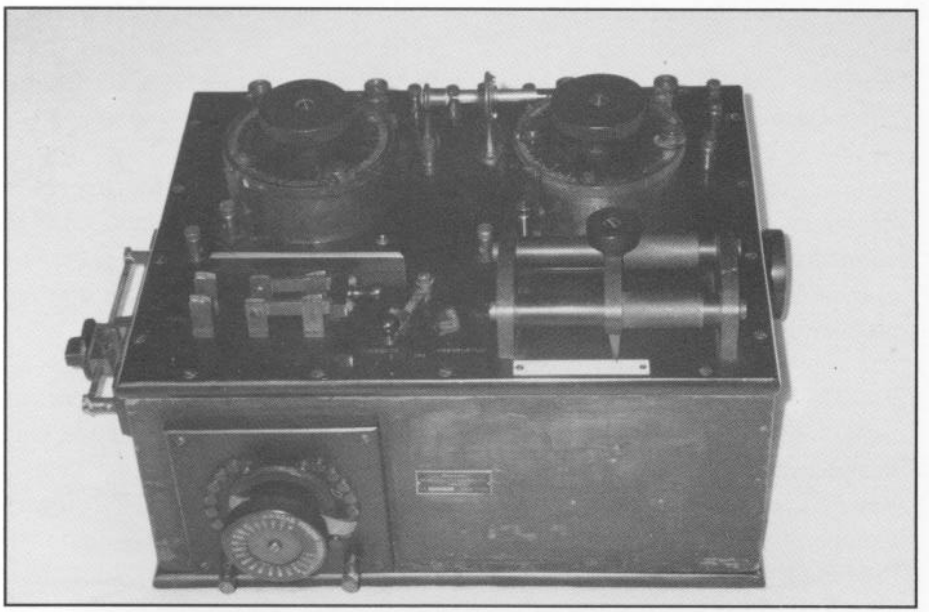


Figure 81. The Marconi Type 103 crystal receiver. It tunes from 200 to 600 meters and uses a carborundum detector. Designated primarily for marine applications, it was built entirely from English Marconi components.
Source: Jim Chew Collection

Figure 82. The external crystal detector for the Type 103 receiver. It uses a cup containing both carborundum and cerusite minerals. A brass loop is incorporated, which, when locked onto an operating table, made it difficult to put in your pocket for your own use. Source: Kreuzer Collection

To attempt to describe in detail the apparatus produced would require a large book, for it was always changing. By comparison, United Wireless had essentially the same spark transmitter and only five different receivers from 1907 to 1912, Types A, B, C, D, and E.

A policy change was now instituted by the Commercial Manager of the American Marconi Company, the young David Sarnoff. Previously the company would only lease its equipment; now it was decided to sell it outright. One of Sarnoff's many brilliant moves, the new policy resulted in a sizable number of orders being placed by the U.S. Navy in 1913.

Prior to this time, British designed and engineered equipment was being used in all the Marconi installations. Harry Shoemaker brought many designs and ideas from United Wireless, and the United Wireless "Type D" tuner was placed in service, with the addition of a Marconi Wireless Telegraph Company name tag. This receiver became part of the auxiliary equipment described in the *Instructions For Marconi Operators*, printed in June, 1913. (See Fig. 72)

Many receivers were produced from 1912 until American Marconi's absorption by RCA in 1919. They began with the Type 101 and ended with Type 122. The first receiver designed by Harry Shoemaker for Marconi was the

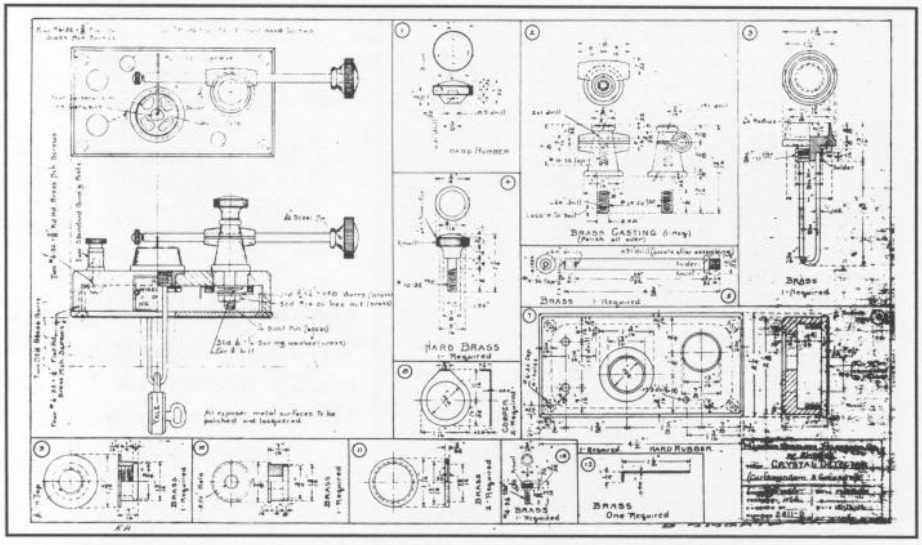


Figure 83. Original blueprint for the detector in Figure 82. It is dated December 12, 1912 and was among the first items produced at the Aldene plant. Source: Kreuzer Collection

Type 101, intended for land stations equipped with 5-kW transmitters. Its design derived from the United Wireless Type "E" tuner, which contained a loose coupler on its panel and covered the frequency range of 200-500 meters. The 101 used a loose coupler mounted behind the front panel and incorporated two solid rectifier detectors, cerusite and carborundum, on the front panel. Less than 100 of these sets were manufactured.[83]

A few Type 102s were produced, which tuned from from 200-4000 meters. The Type 103 was assembled from British components; patterned after the Fleming valve receiver, it covered from 200 to 600 meters. It used a carborundum detector with provision for an add-on cerusite detector. Although the carborundum detector was considerably less sensitive than the cerusite, it had an advantage of increased stability and wasn't easily disturbed by static, loud signals or vibrations.

The 103 was a very popular receiver, but by January of 1915 instructions were sent to technicians and operators for changes in the design, resulting in a new model, the Type 107. The tuning circuits were completely overhauled, with a resulting coverage of 250 to 4,000 meters.[84] By November of 1915 new orders detailed the reconstruction of the remaining Type 103 and Fleming valve tuners to allow reception of wavelengths up to 2,800 meters. After either type was altered according to the instructions, it became known as the Type 107-A, and is easily identified by a six-point, double-throw switch

Figure 84. Marconi Type 22 wavemeter, covering from 200 to 750 meters. It is dated 5/20/14 on the nameplate.
Source: Kreuzer Collection

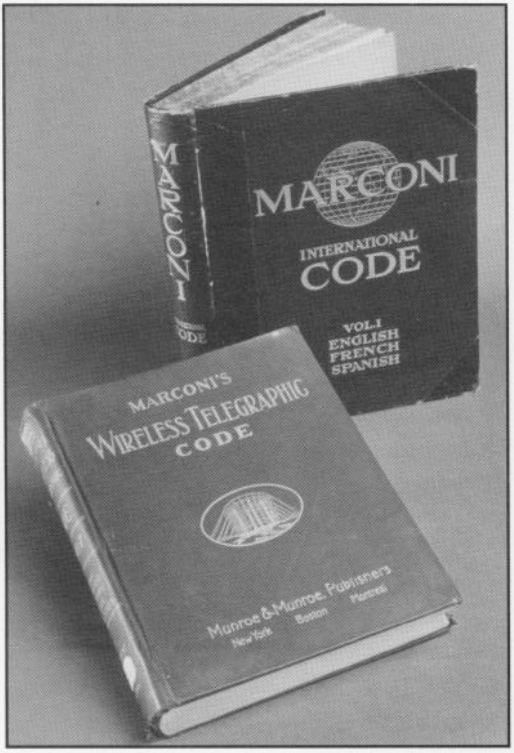


Figure 85. Marconi code books which were used at all wireless stations to facilitate the handling of messages. The standing book is from 1919, while the other is 1906-7.
Source: Kreuzer Collection

mounted on the top panel. As a result, unaltered Fleming valve and Type 103 receivers are very scarce.[85]

While researching the George Clark *Radioana* collection at the Smithsonian archives, the authors came across an interesting box of Marconi ephemera which included details of the factory. The first report is a listing of every employee involved with the manufacturing of wireless equipment at the Aldene, New Jersey plant, including their salaries. As an interesting sidelight, listed below is a sampling from the report, which is dated June 27, 1913, and includes a total of 187 workers.[86]

A.Y. FORREST	LABORATORY WORKER	$21.92 PER WEEK
H.D. BENSON	101 RECEIVER	$20.00 " "
S.M. BUDD	CHAUFFEUR	$18.00 " "
P. KREISS	VALVE TUNER	$17.00 " "
TOM WIER	TOOL ROOM	$8.00 " "
K. ULRICH	WINDING TRANSFORMER	$6.00 " "

The other report consists of ten pages, listing 193 employees and their duties, dated December 24, 1913. Here is one entry:[87]

LATHE HAND	24 WORKMEN
101 RECEIVER	21 "
VALVE TUNER	3 "
WAVEMETER	10 "
DISC CONDENSER	4 "
KEYS	3 "
ENGRAVING	2 "
BILLI CONDENSERS	2 "
ROTARY SPARK GAP	2 "
HELIX OSC. TRANSFORMERS	3 "
HIGH POWER STATIONS	5 "
CHAUFFEUR	1 WORKMAN

Probably the first Marconi receiver to use a three-element vacuum tube was the Type 105. The tube used was a Marconi Type "D", which bore a close resemblance to a double-wing DeForest spherical audion. Needless to say, DeForest soon filed a suit against Marconi claiming infringements of his patents, but before the case ever made trial, the Marconi Company confessed its guilt in the matter. The 105 was put on the market in early 1915 for receiving long wave, from 300 to 6,000 meters.[88]

During 1914 the new Marconi works at Aldene, N.J., was very busy bringing out many new designs, among them the 1/2-, 2- and 5-kW 500-cycle quenched gap transmitters.They needed a new receiver for smaller installations,

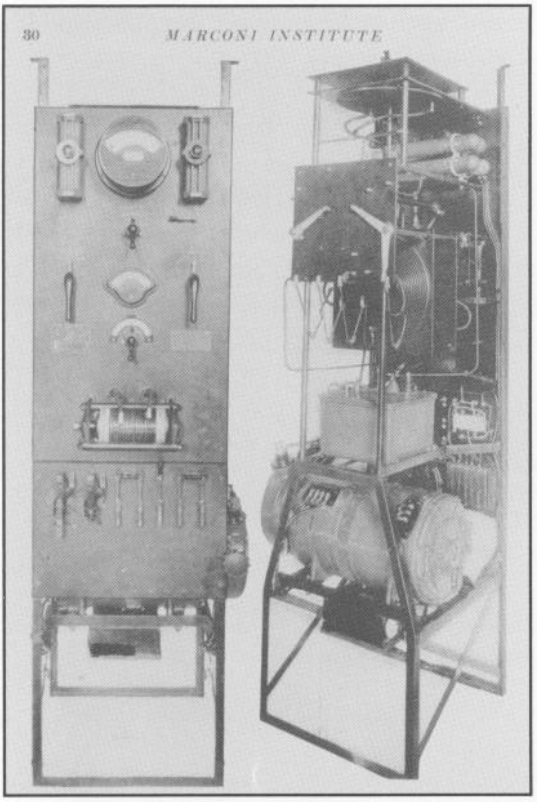


Figure 86. Marconi Type P-5 1/2-kW, 500-cycle quenched-gap spark transmitter. It was designed for shipboard use and covered from 300 to 600 meters. Source: *Manual Of The Marconi Institute*

both for government orders and private rentals. (At this time Marconi did not sell apparatus to private users—most ship installations were on the basis of one thousand dollars a year rental.)[89]

The new receiver was the Type 106. Of the same general appearance as the earlier 101 and 102, it was smaller and tuned from 200 to 3500 meters. Most of the design work was done by Roy Weagant, but Fred Sammis and Harry Shoemaker also had a hand in it. The earliest 106s sported an engraved panel while later models used etched metal dials and plates, the result of faster production during the war years.[90]

The 106 receiver was marketed early in 1915 and used for many years, with updated versions of the 106B, the 106C and finally the RCA 106D. It was still used aboard ships until January of 1942, when they and all other regenerative receivers were outlawed for marine use for fear the radiated energy might be picked up by enemy direction finders on submarines.

By the end of March, 1915, the Marconi Company had 225 coast stations and 1,894 ships equipped with their wireless apparatus. By mid-1915 Roy Weagant had replaced Frederick Sammis as the chief engineer, and

Figure 87. Marconi Type 106 receiver, probably the most popular of all Marconi receiving sets. It lasted for many years, going through numerous changes in both design and type numbers (106B, 106C, 106D).

Source: Kreuzer Collection

Sammis returned to his homeland to be with his parent company, British Marconi.[91]

The Aldene plant provided all the apparatus accompanying receivers and transmitters, such as spark gaps, telegraph keys, wavemeters, antenna switches, and Leyden jars. The last series of receivers was produced for the Signal Corps in 1918 and 1919 and were designated Types 120-121-122. They are identical in appearance, differing only in wavelength. As an example, the Type 120 covered 50 to 225 meters, while the Type 122 covered 175 to 775 meters.

The American Marconi Company was nearing its heyday. Over a quarter of a million commercial messages were sent in 1915. This traffic was brought almost to an absolute standstill, however, in early 1917, when war with Germany was declared. All wireless stations were affected, either by being completely shut down or put under United States Navy control.[92]

At the time 540 ships had Marconi apparatus. The U.S. Navy took over 370 ocean going vessels. Although the remainder were left in Marconi's control, the vast majority of the communications business was crippled.

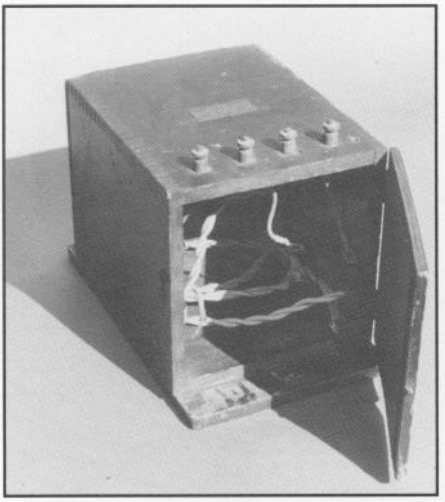


Figure 88. Marconi Type 106 battery box. The blueprint shows this to be the battery holder that was stored under the operating table.
Source: Kreuzer Collection

The Aldene factory was to take up the slack through manufacturing. It doubled in size during the summer of 1917, accommodating the orders for wireless equipment to outfit the Army and Navy. Employee growth more than tripled from 200 to 700.[93]

The first million dollar contract was awarded for 400 1/2-kW, 500-cycle spark transmitters (Type CM 296A) to equip submarines. Larger transmitters were later ordered for battleships and destroyers, while portable units were requested for truck and field use. Equipment sales grew to an all time high of $7,000,000 by 1918.[94]

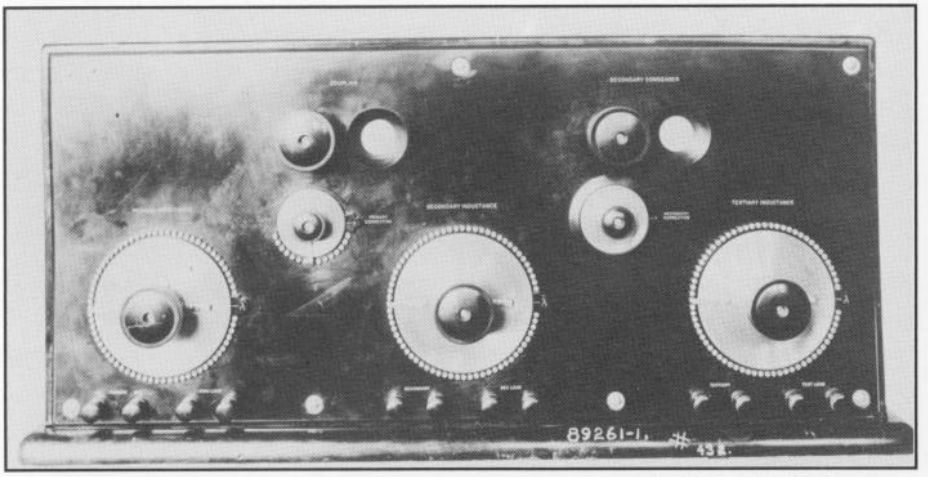


Figure 89. Marconi Type 110 receiver. A prototype built in 1917, it never went into production. Source: George Clark *Radioana* collection

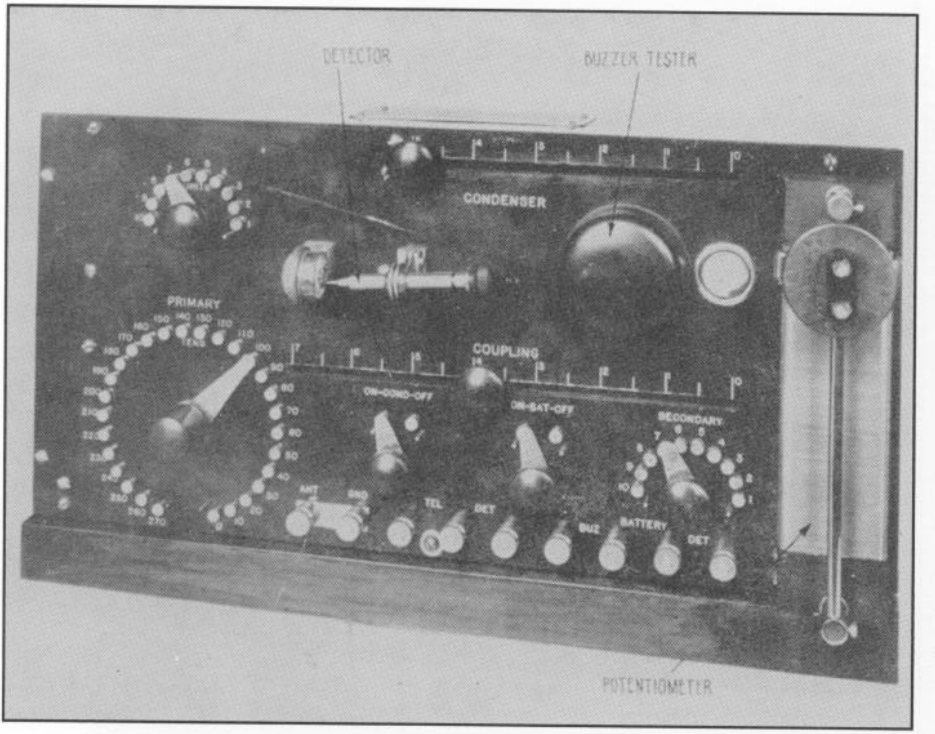


Figure 90. Marconi Type 112 receiving set. This compact set tuned from 200 to 3,000 meters and included a loose coupler behind the front panel. It was designed to be a part of a 1/4-kW installation destined for British ships in 1917.
Source: *The Wireless World*, October 1917

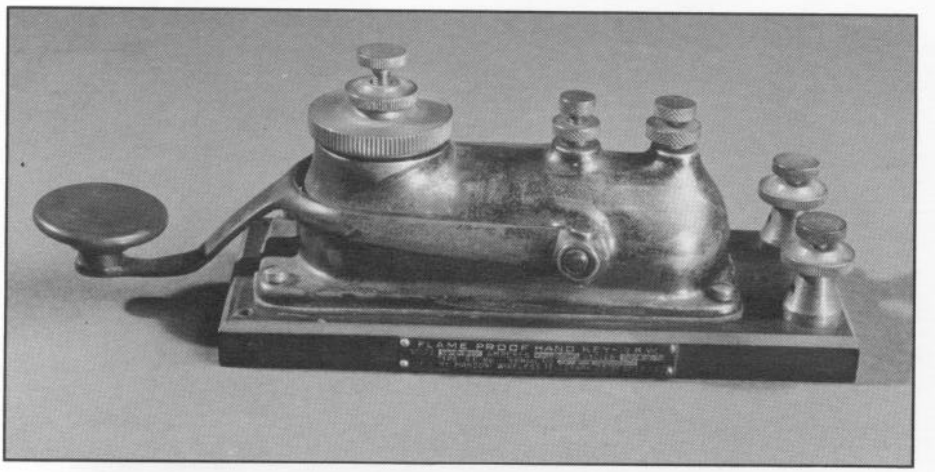


Figure 91. Type SE-86 flame proof 1/2-kW hand key. This well built spark key is rated at 5 amperes and was designed for use where open spark is not permitted, i.e., an airplane cockpit. Source: Kreuzer Collection

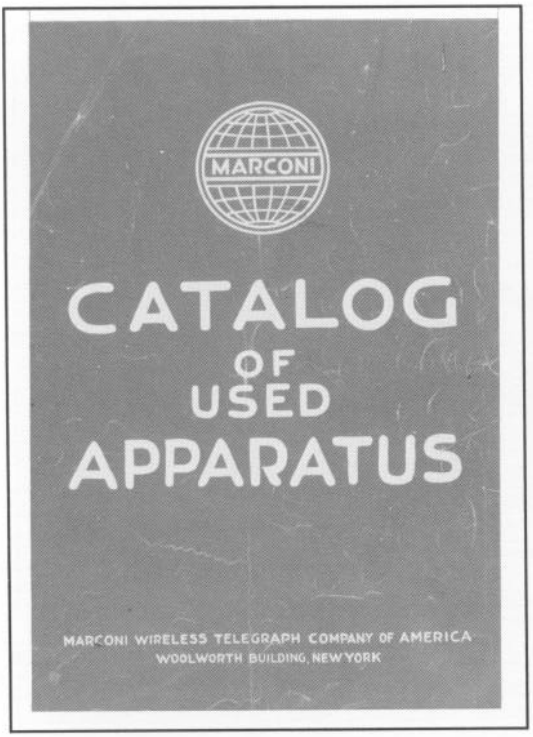


Figure 92. Published around 1916, this catalog lists the out-of-date and used Marconi equipment available at a substantial discount.

Source: Kreuzer Collection

8 MARCONI USED APPARATUS
Type E Receiving Tuner No. 211
Excellence of mechanical construction and efficient design makes possible with this tuner the reception of wave lengths between 300 and 3,000 meters. Fitted with binding posts for antenna and ground, binding posts for receivers, detector stand, variable condenser, potentiometer, battery and reversing switch. Sold complete with box-mounted crystals.
Special Sale Price $40.00
Short Wave Condenser No. 210
Used for reducing the wave length of the antenna system to a value below the natural period. The type shown has been carefully designed to withstand considerable voltages. Condenser includes four high potential plates connected in series. Recommended to amateurs who wish to make their sets comply with Government regulations.
Capacity ..... .0005 microfarads
Special Sale Price $3.00
Head Telephones No. 212
Sensitive and reliable 2,000-ohm receivers with adjustable headband. Equal to any on the market.
Special Sale Price $4.50
Aerial Change-Over Switch No. 213
Substantial and complete; controls both transmitting and receiving circuits, allowing the antenna to be employed for transmitting and receiving as desired.
Special Sale Price $3.50

Figure 93. A page out of the Marconi catalog showing aUnited Wireless Type "E" tuner for sale at $40.00. Other items listed include a Type "D" tuner for $6.75, a 10" spark coil for $65.00 and a rotary spark gap for $18.00!

Source: Kreuzer Collection

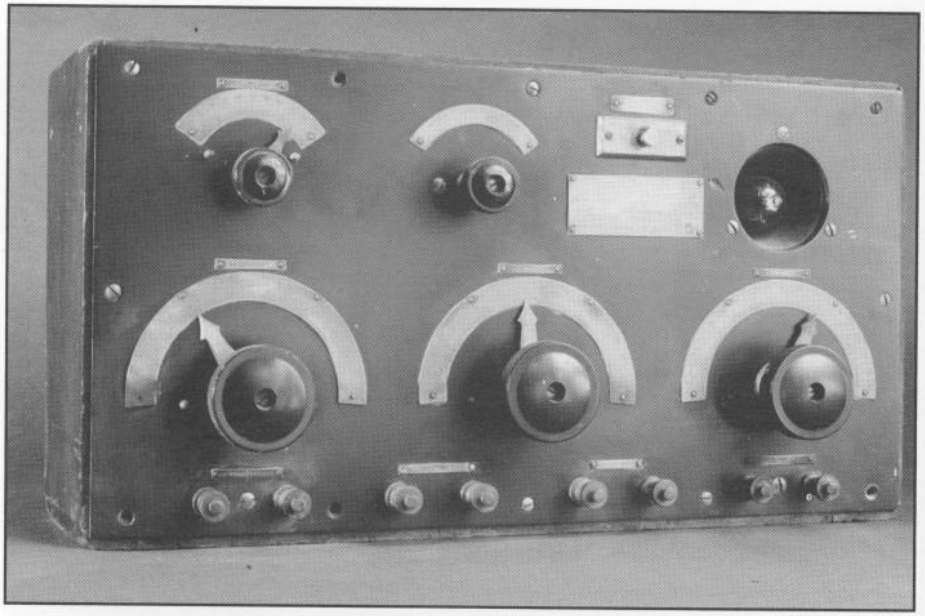


Figure 94. Type 122 receiver. Built for the War Department - Signal Corps in 1918, this was one of the last complete receivers made by American Marconi.
Source: Kreuzer Collection

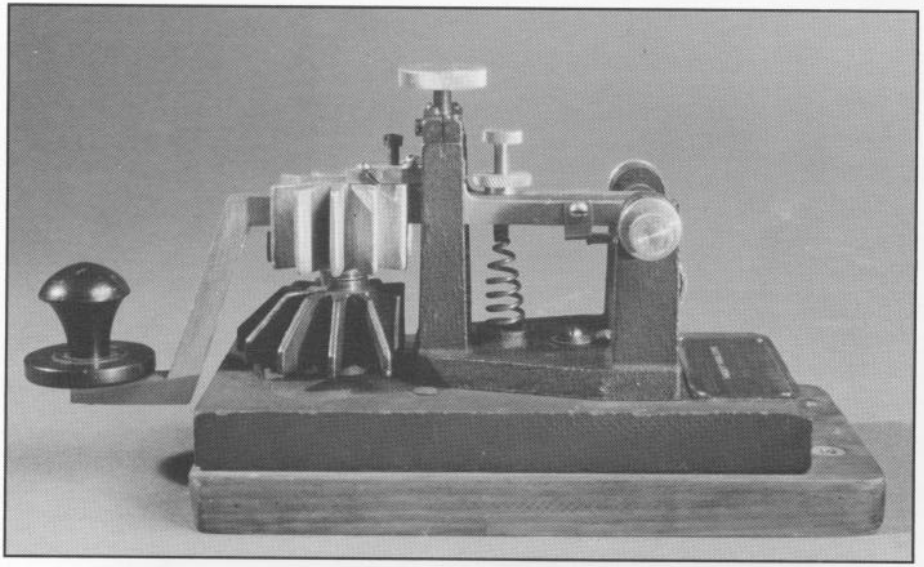


Figure 95. A 5-kW auxiliary hand sending key, rated at 50 amperes @ 250 volts. This was built for the War Department - Signal Corps in 1917. It is one of the largest and heaviest keys made by Marconi, and is mounted on a slate base.
Source: Kreuzer Collection

Figure 96. Marconi Type CM 2946C Short Wave receiver made for the Navy Department, Bureau of Steam Engineering. It covered from 250 to 3100 meters and was built in 1917. A popular battleship receiver, many were manufactured during the First World War. Source: Kreuzer Collection

Figure 97. A jacket worn by a Marconi wireless operator during the 1910-1919 period. The wireless man must have been of a small stature, as this fits Felicia, who stands 5'6" tall!

Source: Kreuzer Collection

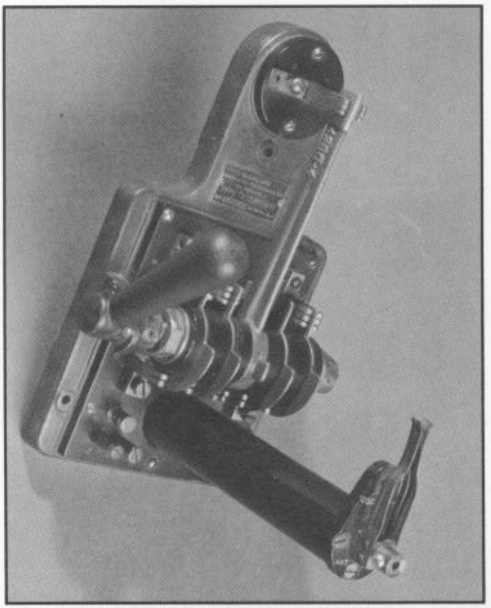


Figure 98. Type "I" antenna switch used in the 1/4- and 1/2-kW wireless stations of the WWI period.
Source: Kreuzer Collection

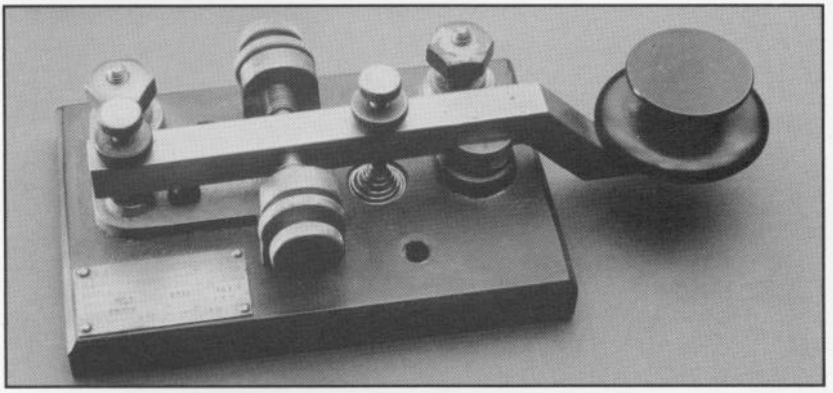


Figure 99. Type CM 425 1-kW auxiliary hand sending key, made for the Navy Department, Bureau of Steam Engineering. Dated 1917, this key is rated for 20 amperes @ 250 volts. Source: Kreuzer Collection

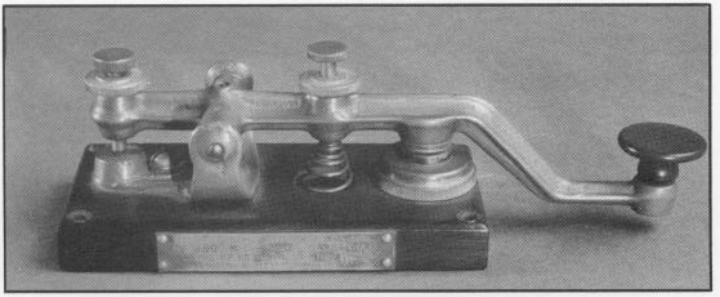
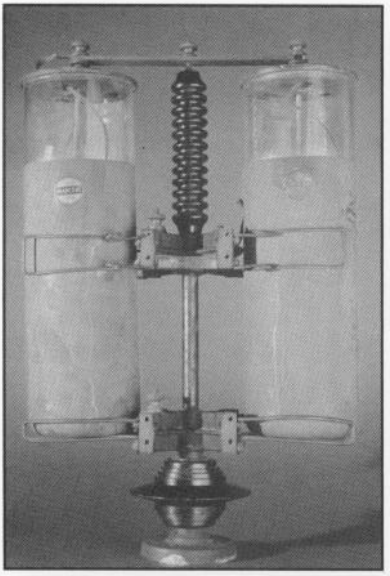
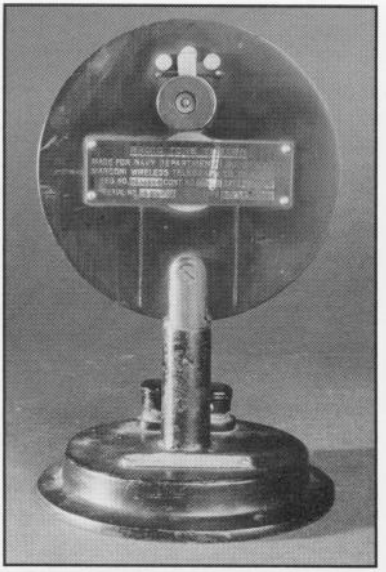
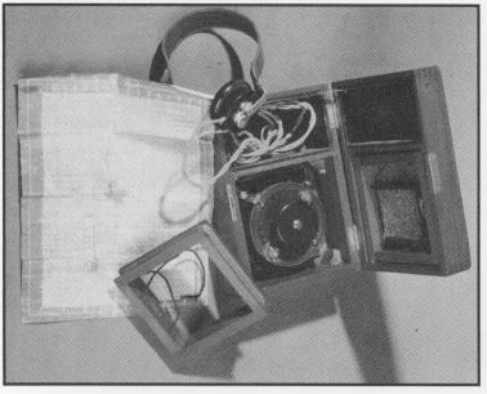


Figure 100. Type SE 68 auxiliary hand key, made for the U.S. Navy. Produced in 1917, this key is rated at 20 amperes @ 250 volts. Source: Kreuzer Collection







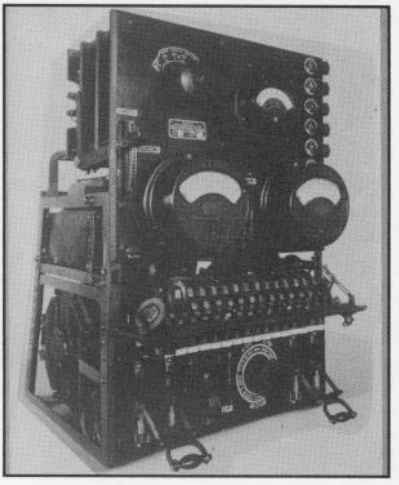


Figure 101. (Upper left) A pair of Marconi transmitter Leyden jars, each rated at 0.002 mfd. They are mounted in a Type SE 150 two-jar rack manufactured by the Machinery Division, Boston Navy Yard. Source: Kreuzer Collection

Figure 102. (Upper right) Radio Tone Tester Type SE 84, built for the Navy Department, Bureau of Steam Engineering, in 1918. This device enabled the operator to monitor the output of his spark transmitter by using a crystal detector mounted on the back. Source: Kreuzer Collection

Figure 103. (Lower left) A portable wavemeter with spare pickup coil, blueprint and original headphone. Most Marconi wrieless stations had one for determining the wavelength of a circuit. Source: Kreuzer Collection

Figure 104. (Lower right) The Type CM 296A 1/2-kW, quenched-gap spark transmitter, tuning from 300 to 952 meters. Source: *Marconi Maintenance Manual*

Figure 105. A pair of American Marconi headphones, identified on the earpiece. Note the Navy type headband and the length of the phone pins. This set may have been used at the Aldene factory.
Source: Kreuzer Collection

The Armistice was signed in November, 1918, signaling a change in the wireless communication business in the United States. By November of 1919, one year after the end of the war, the American Marconi Company had reached the end of its life; the formation of RCA was imminent.

MARCONI'S WIRELESS TELEGRAPH COMPANY OF CANADA, LTD.

THE MONTREAL, CANADA, FACTORY

The first permanent wireless station in Canada was the Glace Bay transatlantic station. Completed in December, 1902, it would eventually prove to be a financial drain on the company. Successful transatlantic two-way communication with Poldhu was still a few years down the road. Progress had been made equipping ships with wireless apparatus, so the Company decided to eliminate the experiments at the Glace Bay and Poldhu stations. The time had come to develop a new transatlantic service for shipping.

Many of the various steamship lines carried Marconi apparatus, including Cunard, White Star, Red Star and the American Line. It was advantageous for ships to be able to contact a shore station and alert the home office when they were due to arrive. In the event of mechanical trouble or an accident at sea, as more ships carried wireless, the probability increased greatly of another vessel coming to their aid. By October of 1905 there were 74 passenger steamships carrying Marconi apparatus.[95]

As business increased in Canada, a decision was made to create the Marconi Wireless Telegraph Company of Canada. Originally registered in Ontario on November 1, 1902, it obtained a Dominion Charter by a Special Act of Parliament on August 13, 1903.[96]

The Company was originally owned almost entirely by Marconi's Wireless Telegraph Company, Limited of London, England, and under an

agreement entered into between the two companies in 1903, the Canadian Company was granted rights in perpetuity in Canada and Newfoundland under the patents of the Parent Company.[97]

By May, 1904, the MWT Company of Canada received a contract from the Canadian government for the erection, installation and operation of a system of wireless telegraph stations along the St. Lawrence River and the Eastern Canada coast line. The contract called for payment on a royalty and license basis. The apparatus used by these stations was constructed in the machine shop at Glace Bay. The shop also made parts and performed repairs for the transatlantic station. It was the first to manufacture commercial radio equipment in Canada.[98]

During a visit to the Glace Bay station in September, 1906 Marconi designated $40,000 to be spent improving and enlarging the company's machine shop. He felt it would increase efficiency by having his Glace Bay technicians design and manufacture the wireless apparatus directly at the station. He was also bound by a promise made to the Canadian government to build as much apparatus in Canada as possible.[99]

By early 1907 the machine shop was turning out magnetic detectors, switchboards, high frequency transformers and smaller instruments for the Canadian coastal stations. The first shop manager, Mr. Warren, was very adept at designing the unusual, welcoming every opportunity to overcome obstacles.[100]

The orders continued to roll in over the next three years. By 1910, the Glace Bay shop had far exceeded its capacity to produce. Instead of expanding, it was decided to transfer this phase of the company's activities to the company headquarters in Montreal. It came as quite a shock to the Glace Bay community, for by 1910 there were forty men employed at the machine shop, constructing and designing wireless apparatus.[101]

A suitable plant, with space for test and draughting rooms was found on Delorimer Avenue. The regular staff at first consisted of two machinists, two assemblers and a messenger . It was operated under the supervision of the chief engineer, and any members of the engineering staff who chanced to be in Montreal were employed in testing apparatus and drafting plans for new equipment, or new stations.[102]

About the middle of 1912 the company began to manufacture for itself equipment which had been previously purchased from others. Such pieces of

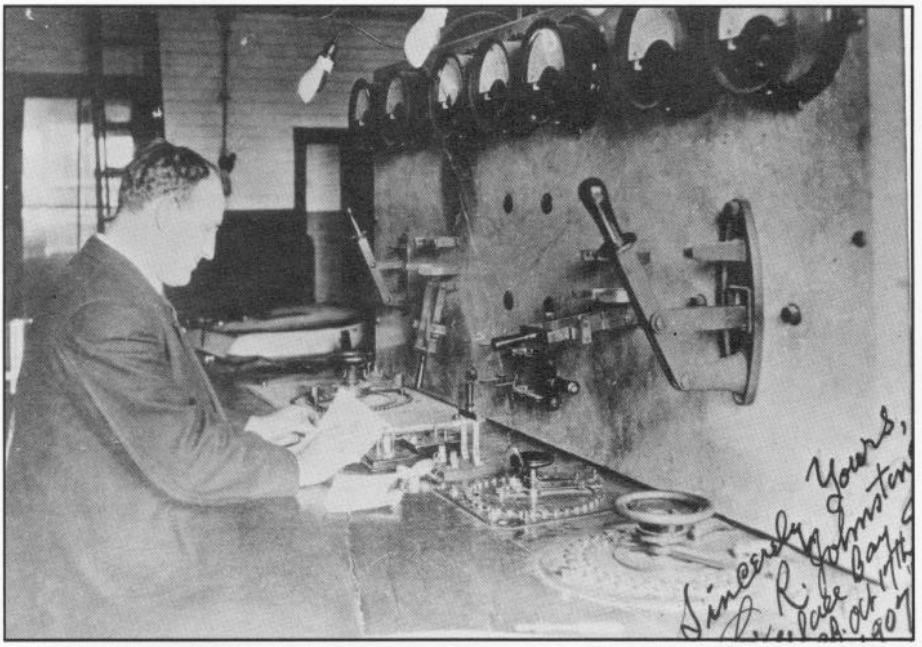


Figure 107. L.R. Johnstone transmitting the first official messages from the Glace Bay station on October 17, 1907. The front cover (Fig. 106) shows the receiving station at Glace Bay. Source: Marconi Company Archives

apparatus as switchboards and complete receivers were now being made entirely in the Montreal plant, and plans were being prepared by the local engineering staff for all new Canadian stations. The first three large stations on the Great Lakes were designed and built this year, at Tobemory, Midland and Sault Ste. Marie. The next year saw the construction of two other stations at Les Pas and Port Nelson in connection with the building of the Hudson's Bay Railway."[103]

A large amount of equipment was designed and constructed at the Montreal plant, as evidenced by the numerous blueprints and line drawings which have survived. Here the first synchronous spark gap transmitter was made for the government wireless station at Grindstone, Magdalen Islands. The much-heralded Type 843 receiver was also built here. It incorporated a combination of two different circuits, short wave and long, each with its own crystal detector assembly containing multiple minerals.[104]

By the end of 1913 the company had outgrown the Delorimer Avenue factory, and a three-story building on Rodney Street was acquired to accommodate the designing and manufacturing of wireless equipment for World War I.

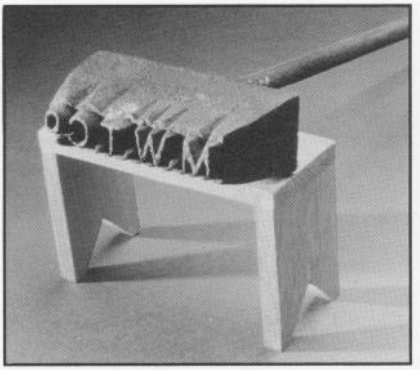


Figure 108. Marconi Wireless Telegraph Company branding iron. This was found, still in use as a stovepoker, in 1983 at the Glace Bay site. A Mr. Russell Cunningham bought the property from the Marconi Company in 1945 and was still living there, amongst all the priceless treasures!

Source: Kreuzer Collection

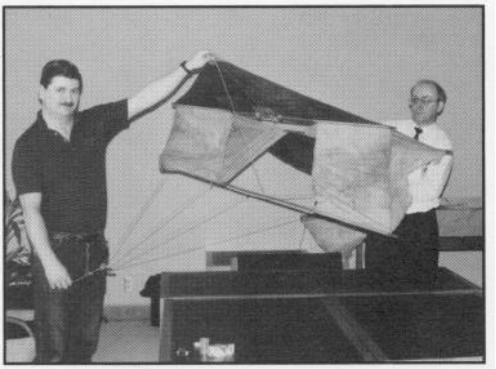


Figure 109. A very early kite unearthed at the Canadian Marconi Company, in storage with five others for many years. James Kreuzer is on the left, while Mr. Roger Hart, the discoverer of the kites, is on the right.

Source: Canadian Marconi Company

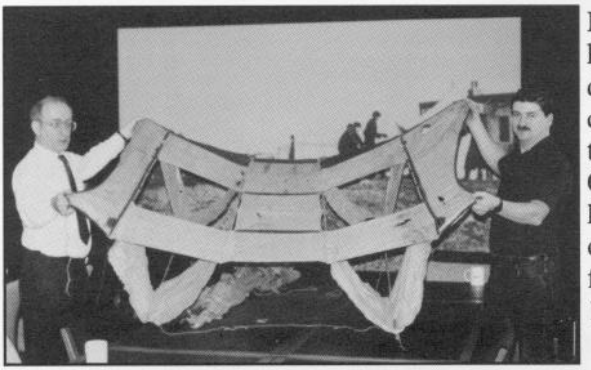


Figure 110. Another vintage kite of an entirely different design, but of the correct construction of a kite from the turn of the century. Could these be some of the kites that Marconi brought over to St. John's, Newfoundland, in December, 1901? Source: Canadian Marconi Company

Figure 111. A vintage tag attached to one of the kites; it reads "#17 Marconi Kites." Source: Canadian Marconi Company

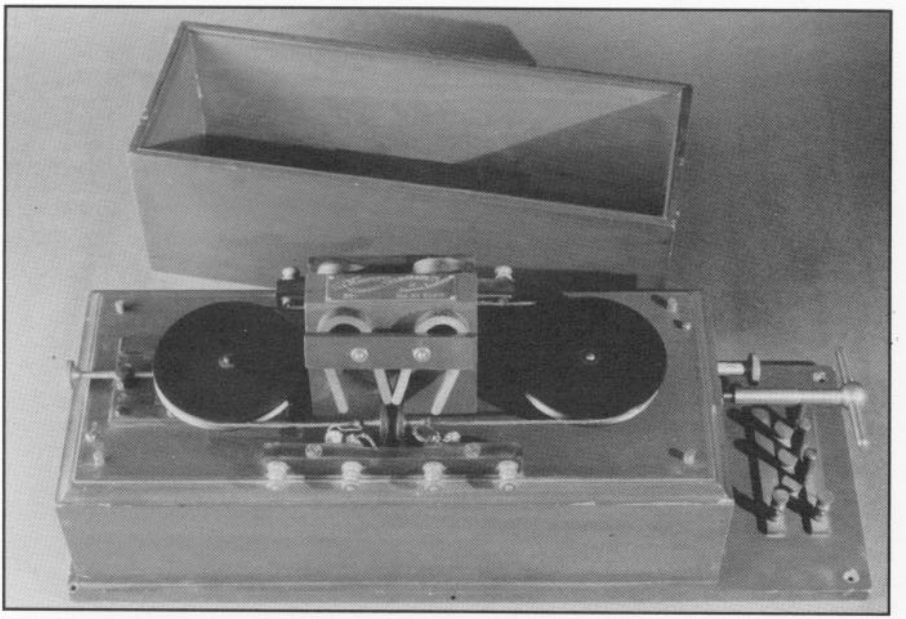


Figure 112. Marconi Wireless Telegraph Company of Canada, Ltd. magnetic detector, circa 1906. The Canadian Marconi version has the phone condenser mounted on an extension of the baseplate, as opposed to the English version which is contained in a separate box. This particular "Maggie" came from Thorn Mayes. He obtained it from a Marconi operator who worked at the Cape Race station, and who told Thorn that it was the one in use at the time of the Titanic disaster, and was in contact with the ship as it collided with the iceberg.
Source: Kreuzer Collection

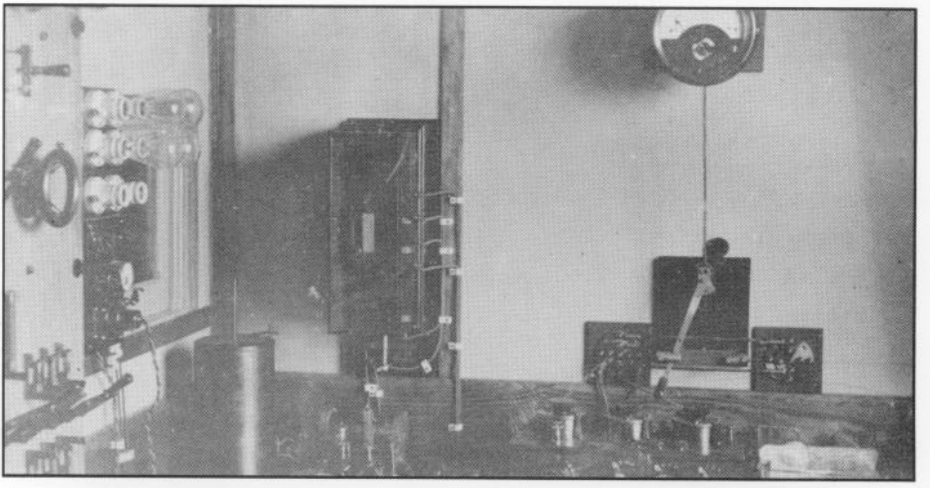


Figure 113. A photograph showing the wireless room at the Cape Race station. Notice the Maggie on the wall, and a multiple tuner on the lower right side.
Source: Roger Hart Collection

Figure 114. A Canadian Marconi stock certificate made out to Marconi's Wireless Telegraph Company for 460,000 shares! It was signed by J. Bottomley and dated April 29, 1912.
Source: Kreuzer Collection

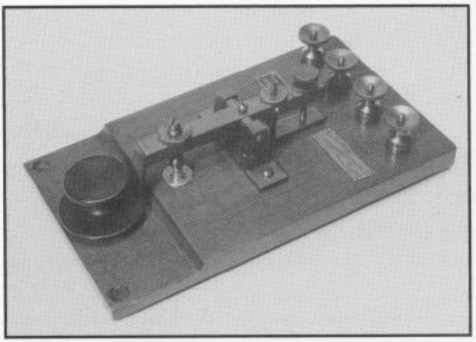


Figure 115. Type 701 Canadian Marconi spark key, circa 1913. This type was used at the wireless installations around the Great Lakes and along the Eastern Canada coastline.
Source: Murray Willer Collection

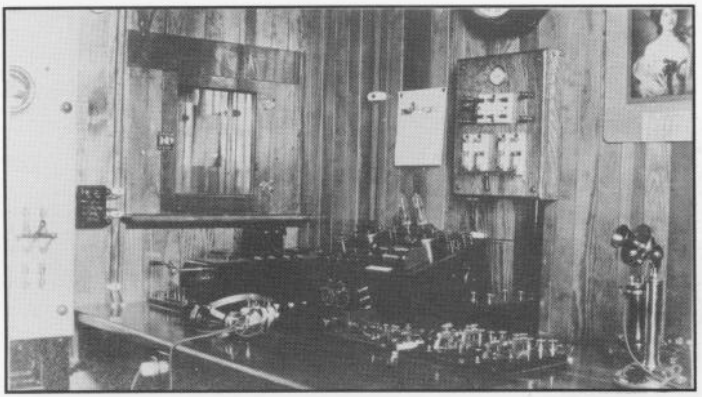


Figure 116. This is the operating room of the Marconi station at Midland, Ontario. Note the Fleming valve receiver and the "Maggie." The calendar on the wall shows October, 1912. Source: Roger Hart Collection

Figure 117. The employees of the Marconi Wireless Telegraph Company of Canada pose for the camera on a cold winter day in Montreal. This photo was taken at the Rodney Street works in 1915.

Source: Roger Hart Collection

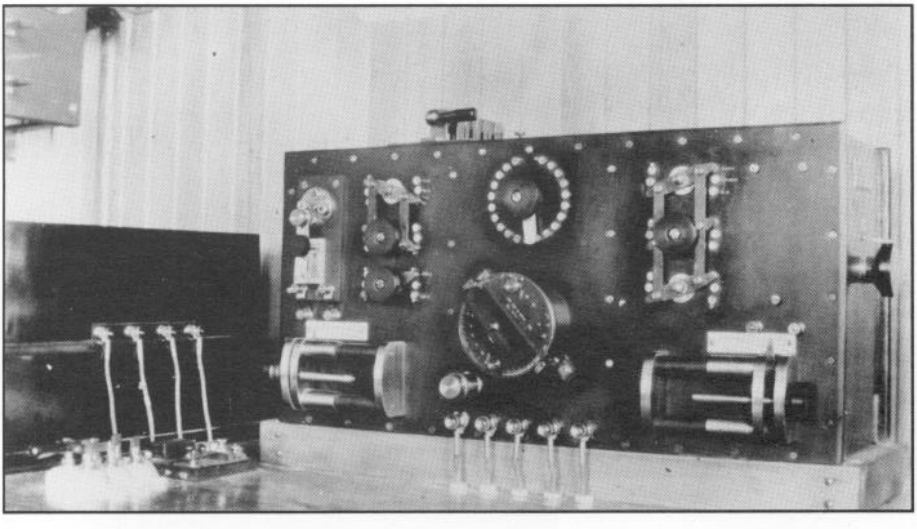


Figure 118. The Marconi station at Kingston, Ontario, circa 1914. Shown is the Canadian marconi Type 843 crystal set and a magnetic detector.

Source: Roger Hart Collection

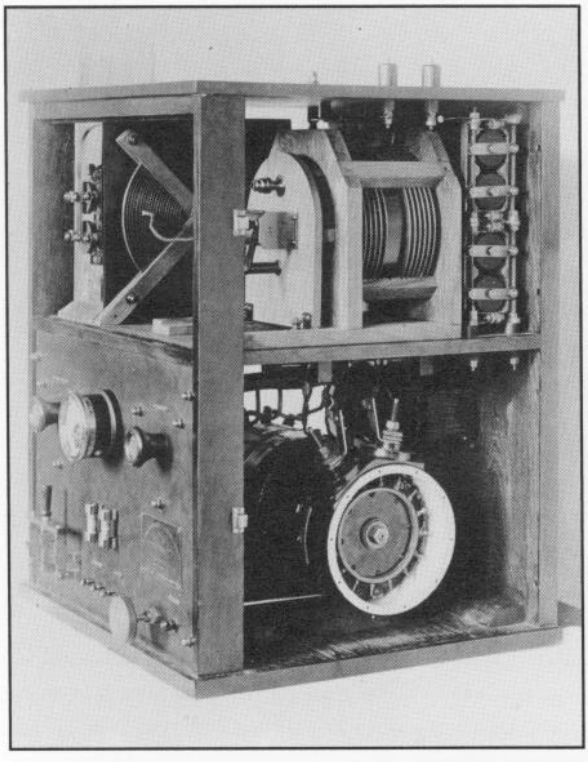


Figure 119. Canadian Marconi 1/4-kW shipboard transmitter using a rotary spark transmitter.
Source: Roger Hart Collection

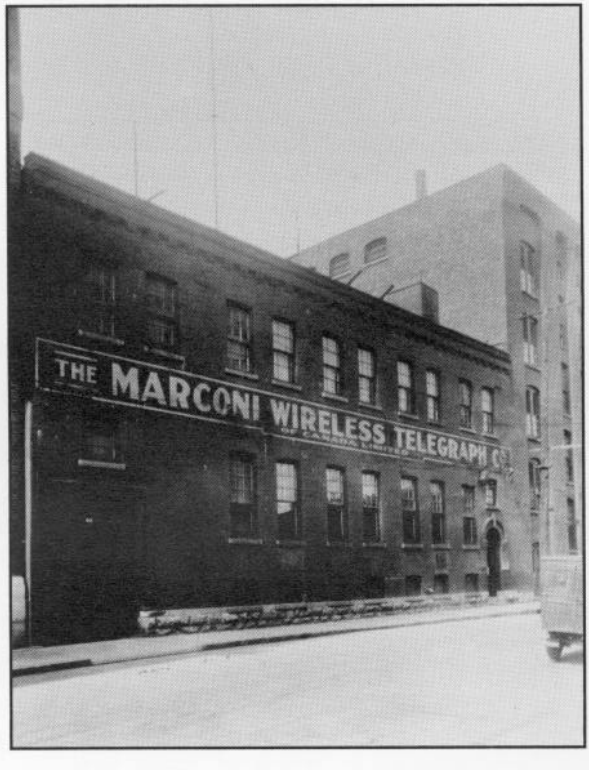


Figure 120. The William Street factory in Montreal. In 1919, from the top floor, far left side, the first broadcasting station in Canada, station XWA, made its transmissions.
Source: Roger Hart Collection

The urgency was so great that the factory was operated day and night, in spite of the difficulty of securing capable employees. Finally, the receipt of large orders from the English company and through it from the United States Shipping Board left no alternative but to increase the manufacturing facilities, and in October, 1917, the plant was moved to a much larger building on William Street, which was equipped to turn out every sort of apparatus required in wireless work.[105]

The William Street plant was where Canada claimed to have initiated the world's first broadcasting station. In early 1919, regular reports were broadcast, including weather reports and general news. With the assigned call letters XWA, the first reports were sent in telegraphic code and consisted of weather reports and some general news. Later in 1919 voice communication was used, and by 1920 the call letters were changed to CFCF.[106]

CONCLUSION

We have traveled with Marconi from childhood experiments, when he made a bell ring to impress his mother, through the major works of his lifetime. Using the most primitive of tools and hand-made equipment, he developed a vision which culminated in possibly the most exciting discovery of the century. Among all the advantages obtained from wireless, Marconi always felt the most important was the ability to save lives.

Marconi was also a creative genius in the world of future communications. He was the forerunner in short wave with his beam system, and while experimenting in 1916, Marconi and C.S. Franklin noted, as Hertz had, the phenomenon of radar as short waves were reflected from obstacles in the signal path.

When we ponder the trials and tribulations involved in developing Marconi's system of wireless, it would seem the impossible had been achieved. He was often disregarded as a serious inventor. He fought nature while attempting to assume control over variable conditions, searching for optimum performance in communications.

His kites failed, he traveled excessively for a family man. The weather rarely cooperated. Against all these odds—and more—Marconi managed to do what no man before him could. He dreamed, then proceeded to make his dreams come true. He was forced

to demonstrate over and over the value of his equipment, often facing ridicule and disappointments. Ahead of his time, he foresaw the possibilities of television. His ideas inspired many others to future inventions. Truly he was a great man.

ACKNOWLEDGEMENTS

Our sincerest appreciation is extended to Roy Rodwell, Curator of The Marconi Museum in Chelmsford and the Photographic Staff of Marconi College, also of Chelmsford, for their excellent assistance with research and photos of the early apparatus. Thanks also go to Doug Penisten for his determination in helping us search for the elusive title of the publication which inspired Marconi to enter the field of wireless telegraphy. We appreciate the opportunities afforded us by the pioneer radio historian, the late George Clark. John Harding of the Smithsonian Archives Center provided an excellent guide to access George's famous *Radioana* collection, a treasure trove of wisdom compiled over a fifty-year period. We have received help with the history of Canadian Marconi from Roger Hart, who has worked there for many years. Jerry Vanicek supplied information on American Marconi, and Henry Bradford of Nova Scotia assisted with Canadian Marconi. Finally, we offer our acknowledgements to the numerous collectors who contributed photos of their rare Marconi apparatus.

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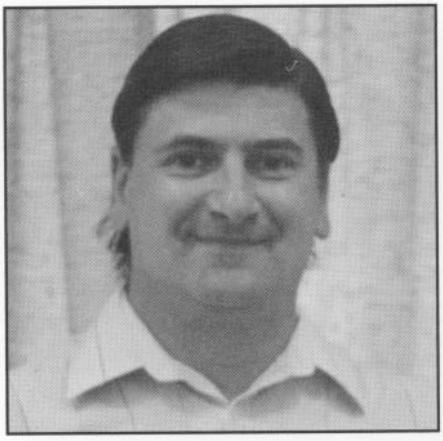
JAMES H. KREUZER, N2GHD

James Kreuzer was born in Buffalo, New York in 1953. Jim's fascination with radio began in 1963 when he purchased his first radio, a Philco 90, at a white elephant sale for 25 cents. He collected a few battery sets from country auctions during the 1960's, but then fell out of touch with the radio scene, substituting drag racing for a few years. From 1974-1980 he and Felicia attended auction sales and flea markets in search of battery sets of the 1920's. In a short period of time the house filled to capacity with radios, parts, tubes and literature. By 1980 Jim was specializing in pre-1920 commercial wireless equipment, especially Marconi apparatus.

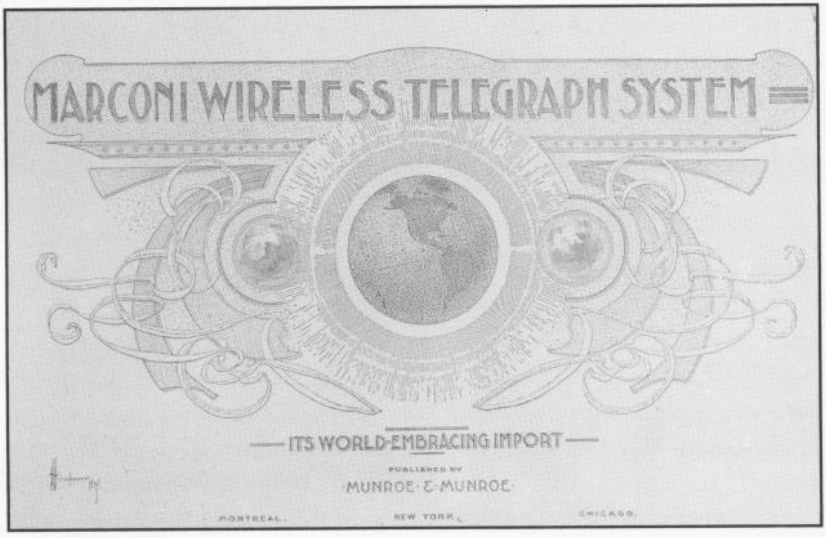
Jim received three years schooling in technical electronics and then worked for eighteen years as a diesel mechanic for Conrail Railroad before starting off on a new career. In 1985 he formed "New Wireless Pioneers" and became a seller of rare and out of print radio, telegraph and electrical books. Jim is a member of The Radio Club Of America, and is respected as an authority on Marconi apparatus. He has acted as an appraiser for the Canadian Marconi Company and the Canadian National Museum of Science and Technology. He and Felicia own one of the most extensive wireless collections and electrical/wireless libraries in the country.



FELICIA A. KREUZER, KA2GXL

Felicia is a native of Minneapolis, Minnesota where she was born in 1955. Felicia joins her husband as an avid collector and historian of early wireless apparatus and literature. A ham radio operator since 1979, she is a Radiologic Technician and is presently training to specialize in Sonography. She is a charter member of the Niagara Frontier Wireless Association and served as its president from 1985 to 1988.

Jim and Felicia have a fourteen year old daughter and a six year old son, who is always picking up transistor radios. Felicia enjoys collecting X-ray apparatus and books, as well as ephemera, especially autographs; the collection now includes letters from Oersted, Morse, Faraday, Maxwell, Hertz, Tesla, Lodge and, of course, Marconi!



The International Contest for RADAR

By
Ed Lyon
Myersville, MD

"...The certain knowledge that in a fortnight one will be hanged tends to focus the mind wonderfully..." ...Samuel Johnson

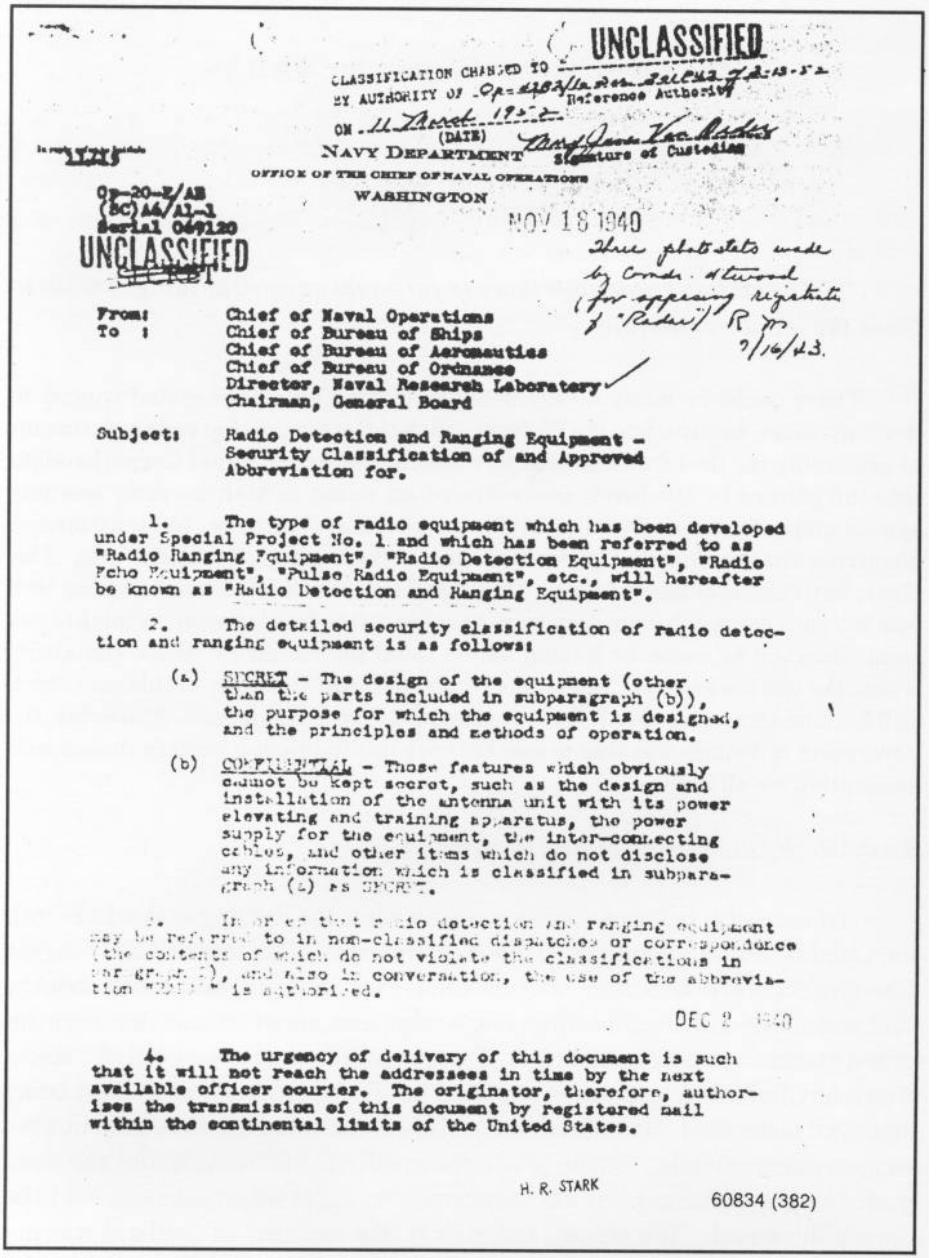
There could be many different books written about the global contest to develop radar. In America, the US Navy led the effort to develop radar as a means of protecting the fleet from air attack, while the US Army Signal Corps, brought into the picture by the Navy, concentrated on radar as both an early warning system and as a means of aiming artillery, especially flak guns. In many foreign countries, the development proceeded amidst the waging of a world war. This story, however, is of limited focus. It is hoped that it will offer an interesting look into the race among the major powers to achieve this development, as might have been observed by someone having access to all the countries' black chambers, where the work was done. The aim here is to describe the irony of this race, for it will become clear that only Britain realized that there was a race. Moreover, the perception in Britain was that to lose the race was to lose the western democratic civilization we all know.

RADAR: RAdio Detection And Ranging

About a year before America was drawn into the fighting in World War II, the Chief of Naval Operations sent a memorandum, classified SECRET, to the Chiefs of the Naval Bureaus and Commands, explaining just how much could be said, outside of classified meetings and workplaces, about a recent development of the Naval Research Laboratory. The new development was called *"Radio Detection and Ranging Equipment,"* and it referred to new systems just being deployed in the fleet. But even this descriptive title was classified, and couldn't be mentioned in public. So the new acronym "RADAR" was created, the word itself being unclassified, but whose meaning was kept secret, and was not to be openly discussed. The memo, and with it, the meaning of "radar," was not declassified until March, 1952, despite numerous public revelations of the radar technique, both official and speculative, in the wartime years.[1]

---

[1]US Army radar research was reported as early as July 30, 1935 in the *New York Times*, and the forewarning of the Japanese attacks on Pearl Harbor and Dutch Harbor, by radar, was reported in the press on August 29, 1945 (*AP*) and June 7, 1942 (*Boston Herald*), respectively. The May 1945 issue of *Broadcasting* magazine reported accurately some of the capabilities of radar, but the information came from Canada, not the US.



UNCLASSIFIED

CLASSIFICATION CHANGED TO
BY AUTHORITY OF Op-[illegible] Reference Authority
ON 11 August 1942
(DATE)
Signature of Custodian

NAVY DEPARTMENT
OFFICE OF THE CHIEF OF NAVAL OPERATIONS
WASHINGTON

Op-20-G/AS
(SC)A4/A1-1
Serial 049120

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SECRET

NOV 16 1940

Three photostats made by Comdr. Haywood (for appearing signature of "Radar") R JS 7/16/43.

From: Chief of Naval Operations
To : Chief of Bureau of Ships
Chief of Bureau of Aeronautics
Chief of Bureau of Ordnance
Director, Naval Research Laboratory
Chairman, General Board

Subject: Radio Detection and Ranging Equipment - Security Classification of and Approved Abbreviation for.

1. The type of radio equipment which has been developed under Special Project No. 1 and which has been referred to as "Radio Ranging Equipment", "Radio Detection Equipment", "Radio Echo Equipment", "Pulse Radio Equipment", etc., will hereafter be known as "Radio Detection and Ranging Equipment".

2. The detailed security classification of radio detection and ranging equipment is as follows:

(a) SECRET - The design of the equipment (other than the parts included in subparagraph (b)), the purpose for which the equipment is designed, and the principles and methods of operation.

(b) CONFIDENTIAL - Those features which obviously cannot be kept secret, such as the design and installation of the antenna unit with its power elevating and training apparatus, the power supply for the equipment, the inter-connecting cables, and other items which do not disclose any information which is classified in subparagraph (a) as SECRET.

3. In order that radio detection and ranging equipment may be referred to in non-classified dispatches or correspondence (the contents of which do not violate the classifications in paragraph 2), and also in conversation, the use of the abbreviation "RADAR" is authorized.

DEC 2 1940

4. The urgency of delivery of this document is such that it will not reach the addressees in time by the next available officer courier. The originator, therefore, authorizes the transmission of this document by registered mail within the continental limits of the United States.

H. R. STARK

60834 (382)

Figure 1. Copy of letter of 16 November, 1940, from CNO to Navy Bureau chiefs defining use of word "RADAR". Based on this letter, the word RADAR was considered unclassified during the war, and so electronic countermeasure equipment, whose design principles should have been kept secret, were openly referred to as "anti-radars", and thus, didn't have to be classified in the factories where they were built. (Copy Courtesy of NRL.)

The Situation

Between 1900 and 1940, five countries independently, and secretly, discovered the basic principles of radar. Although the most fundamental radar tenet, that many objects reflect electromagnetic (or radio) waves, was understood and demonstrated by Heinrich Hertz in 1892, no one immediately looked at a practical application of radio wave reflection, or of exploiting the reflections or echoes. The notion of radar depends fundamentally on these reflections, and all that is needed to produce radar is to transmit a radio wave, and then receive reflections from some object which is "illuminated" by that transmission, measuring the time it takes for the radio wave to have traveled from the transmitter to the reflecting object, and back to the receiver. This time-of-flight of the radio wave energy indicates the distance, or range, to the reflecting object, and the direction from which the reflection signal is received indicates the direction to the object. Thus the object can be detected, and located.

This basic idea may have occurred to Hertz, Marconi, and others, early in the exploration of wireless telegraphy. Indeed, it is very likely that the *radar range equation*, which expresses how strong an echo will result from a given transmitted power level, effective target reflectivity, and transmitter-to-target range was understood by Maxwell and Hertz. This equation (which was classified as a military secret by every nation engaged in the development of radar) simply explains in starkly discouraging terms just how electromagnetic waves weaken as they travel away from their source, owing primarily to simple geometric spreading. In radar, the primary source is the transmitter, and the power in the transmitted radio wave diminishes as it travels to the reflecting object of interest, called the target. There it elicits an echo, which is, in reality, a fresh new source of electromagnetic energy. This echo then has to undergo the same proportional loss of power as it spreads out, traveling away from the target. Only a tiny fraction of it is captured by the radar receiver; the rest goes off in all other directions. By way of an example, consider a one-kilowatt power level being transmitted toward a target of optimum[2] size (and reflectivity) which is one mile away. The power level of the returning echo, as captured by a simple dipole receiving antenna, would be about one hundred-millionth of a watt. If the same target were placed ten miles away, instead of one mile, the power level of the echo received would have diminished by another factor of ten thousand, to a net total of one trillionth of a watt.

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[2]Here we assume a target of one-half wavelength in span, yielding one square wavelength in reflection area. At 30 MHz, for example, this is a radar target of 100 square meters effective cross section.

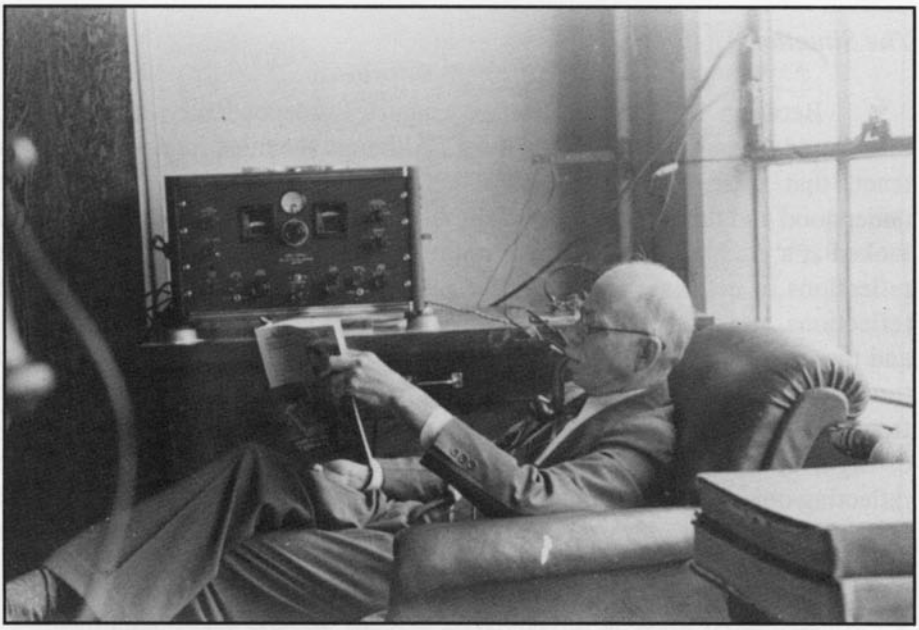

Figure 2. A. Hoyt Taylor in his NRL office in 1946. Note the Super Pro receiver on the table. (Photo courtesy estate of Leo C. Young.)

The realization, by these early experimenters, that the received echo power level they could expect was several orders of magnitude weaker than any they were able to detect with the crude receivers of the day might well have placed radar in the category of "interesting only academically." The first US patent application of a practical application of radio signal reflections being used to measure the range to an object was not filed until that by Heinrich Lowy[3], in July, 1923.

In the 1920s and 1930s, the capability to receive signals which were extremely low in power level was improved significantly, through use of the vacuum tube, especially the pentode, and by using some of the newer receiver circuits, like the superregenerative detector and the superheterodyne.The primary effort thereafter was to reduce the wavelength of the radar signal, so as to approach, in the radar system, a degree of echo resolution and imaging enjoyed by human eyesight. Not that visible-light wavelengths could really ever be reached, but at least that was the aiming point in the radar R&D arena.

The developments in these five nations show some remarkable parallels, if we are to believe everything we read today, after all the benefits of

[3]Patent 1,585,591, granted 18 May 1927.

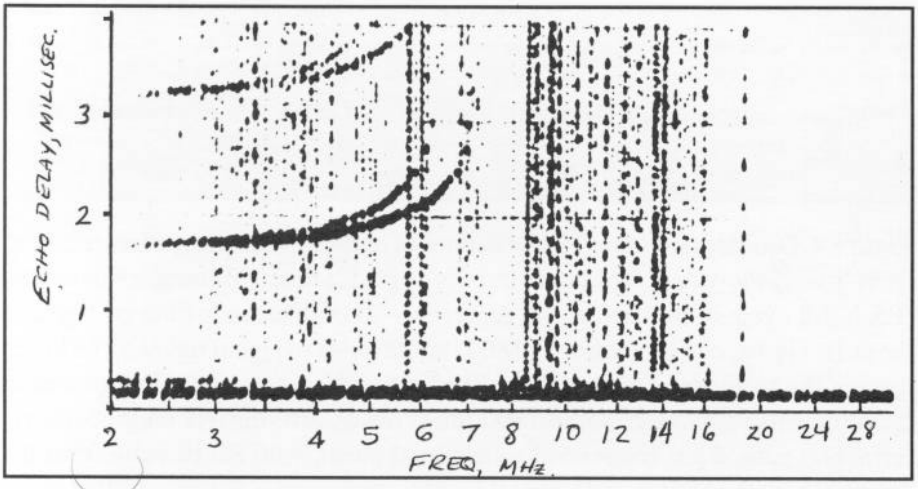

Figure 3. Ionogram from a Bureau of Standards Ionospheric Sounding station, 1961. This is a photo of the CRT showing the height of the ionosphere versus radio frequency. The equipment used was a Barker & Williamson type C-2 ionosonde, built in 1949, which automated the pulse echo experiment by Breit, Tuve, and Taylor in 1925. (Author's original film.)

hindsight are available. This paper uses some modern retrospective reference material, which is so identified, but generally relies on data and writings of the time. The major developments in these countries can be summarized in a few paragraphs:

America:

In 1922, A. Hoyt Taylor and Leo C. Young, of the Naval Aircraft Radio Laboratory at Anacostia, discovered that ships and airplanes deflected radio waves traveling from a transmitter to a receiver.[4] They immediately saw an application: harbor protection. They reasoned that a transmitter on one side of a harbor entrance, with a receiver on the other side, could act as sort of gatekeeper, in any weather or visibility conditions. They wrote a recommendation to their Admiral, who told them to continue their research, and to keep him informed, especially if any better uses could be devised for this phenomenon.

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[4]The only contemporary source regarding this event is Taylor's letter of 27 September 1922 to the Bureau of Engineering over the signature of the Commanding Officer of the Naval Air Station, Anacostia. Retrospectively, we have: Taylor, A. Hoyt, *Radio Reminiscences: A Half Century*, Chapter IX, Dept. of the Navy (Naval Research Laboratory), 1960, and Taylor, A. Hoyt, *The First 25 Years of the Naval Research Laboratory*, NAVEXOS P-549, Navy Department, 1948.

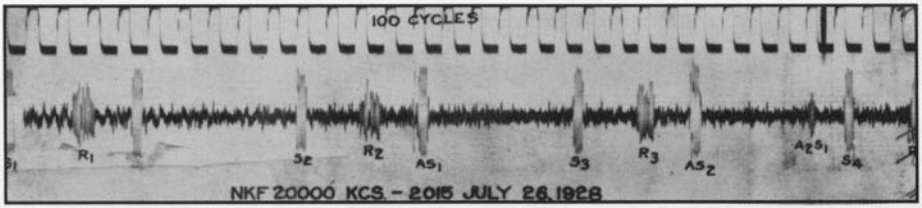

Figure 4. Oscillogram of first pulse echoes of earth surface plus pulses received from 'round-the-world. The upper trace is a 100-Hz time-calibration waveform. (Each full cycle of this waveform represents 10 milliseconds time-of-flight of the pulse signal, corresponding to 1860 statute miles of signal travel.) The lower trace is the receiver i-f signal. S1 is the first transmitted pulse; R1 is its echo from the earth's surface, some 1800 miles away, arriving via an ionospheric refraction path. S2 is the second transmitted pulse, with R2 its echo from the same area on the earth as reflected R1. AS1, however, is the transmitted pulse after traveling all the way around the earth, requiring about 140 milliseconds elapsed time-of-flight (corresponding to about 26,000 miles of travel). S3 is the third transmitted pulse, R3 is its echo from about 1800 miles away, and AS2 is the round-the-world image of S2. Note the pulse A2S1, which is the original first transmitted pulse (S1) after traversing twice around the world, a total distance of 52,000 miles. Operating frequency was 20 MHz. Data taken at NRL station NKF in 1928, by Hoyt Taylor and Leo Young.

(Photo courtesy estate of Leo C. Young.)

In 1925, Taylor and Young, by then situated in the new Naval Research Laboratory (NRL), at Bellvue, D.C., collaborated with Gregory Breit and Merle Tuve, of Washington's Carnegie Institution, to build and operate the first pulsed transmitter/receiver pair to seek radio reflections, the target being the overhead ionosphere.[5] The transmitter/receiver combination operated at frequencies set by quartz crystals, from 2 MHz to about 14 MHz, operating with 200-microsecond pulses. Through these techniques they helped win a scientific race for definite proof of the existence and location of this ionized atmospheric layer, the race being between Breit, Tuve, and Kennelly, for America, and Appleton, Barnett, and Heaviside, for Britain. (For many years, thereafter, the ionosphere was called the Kennelly-Heaviside layer in America, and just the Heaviside layer in Britain.)

By 1930, Taylor and Young had constructed several sets of transmitters and receivers able to collect echoes of pulsed transmissions, and with these they studied the nature of shortwave signal propagation, tracing exactly where the signal energy traveled on its path from transmitter to distant listener.[6] By June

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[5]Dunlap, Orrin E, Jr., *Radar*, pp115ff, Harper and Bros., 1946.

[6]Taylor, A. Hoyt and Leo Young, "Studies of Echo Signals," *Proc.IRE*, V17, No.9, Sep 1929, pp1491ff.

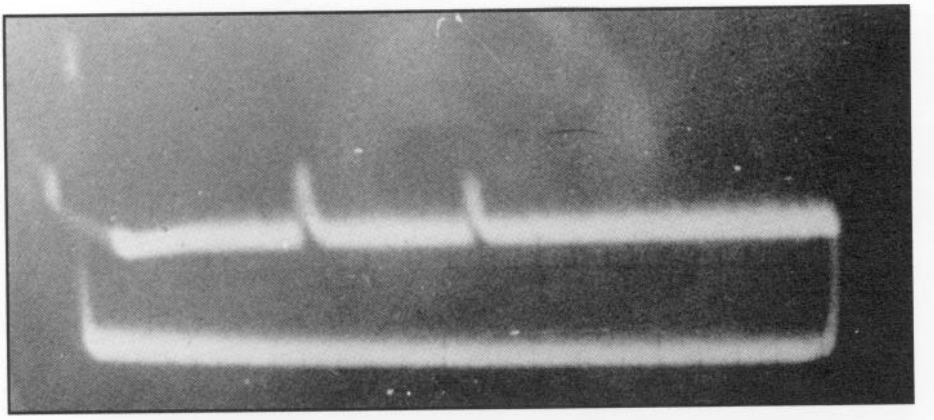

Figure 5. "A" Scope picture of two ship echoes seen on prototype XAF radar aboard *USS New York*, in February, 1939. Upper trace is first 35,000 yards; lower trace continues range scale to 70,000 yards. Leftmost target blip is from two battleships, one hidden behind the other, at about 9000 yards. Rightmost blip is from *USS Texas*, at 17,000 yards range. This prototype radar was copied, exactly, by RCA, as the CXAM, used on all battleships entering the war.
(Photo courtesy estate of Leo C. Young.)

1930, they had built a transmitter/receiver pair operating on 60 MHz that **detected** the presence of airplanes, and by 1934, the project had received some official standing. With this new status, and with a new project leader, Robert Page, NRL devised a pulsed 29-MHz set in 1936 which was widely demonstrated to Navy and Army Signal Corps dignitaries. Meanwhile, the 60-MHz radar was improved sufficiently to allow them[7] to **detect and locate** aircraft flying near Anacostia, D.C. The Laboratory continued to increase the operating frequencies, which increased performance per unit antenna size, until they had a working radar operating at 200 MHz. This was their prototype model XAF,[8] which was placed on the destroyer *USS Leary*, for extensive tests. A single Yagi antenna and NRL's first duplexer (allowing connection of the antenna to both transmitter and receiver) were mounted on one of the ship's 5-inch guns, to allow aiming of the antenna. A second cruise of the *Leary*, for extensive radar tests, had the radar using a "mattress" array of dipoles for the antenna, and this became the configuration of all XAF radars. By 1938, the XAF was put aboard several capital ships,[9] enabling them to survey their surroundings, even in nighttime, in 1938. In the U. S. Navy, as in navies everywhere, advancements in the ability of the fleet to detect and locate unseen aircraft were encouraged, once Billy Mitchell had driven home his point that airplanes could sink ships. This NRL work was carefully evaluated by the Army Signal Corps, for their use in early warning of approaching aircraft.

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[7]Page, R.M., *The Origin of Radar*, p186, Greenwood Press, Westport, CT, 1962.
[8]The contractor-built version of this radar was the CXAM, built by RCA.
[9]Including early tests on the battleship *USS New York.*

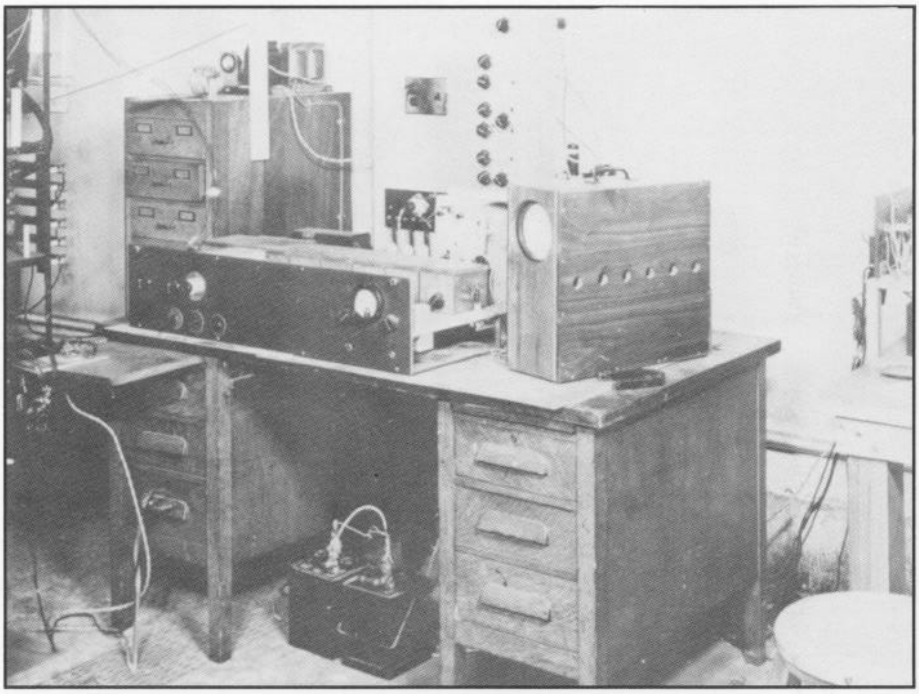

Figure 6. First successful radar receiver, March 1935, built by NRL's Leo Young. Leo had always been impressed by the work of Leutz, and it shows. This superhet operated at 60 MHz, and had a 2 MHz i-f strip having five stages, each using a 78 amplifier tube. This receiver was also used at 200 MHz, by using a preamplifier and converter ahead of the receiver.

(Photo from estate of Leo C. Young.)

By cooperating with RCA and Eitel-McCullough, NRL was able to get excellent new high-frequency tubes for the 200-MHz radar effort, and developed the XAR[10] radar, which had a ring oscillator transmitter using Eimac 327A tubes and an RCA lighthouse tube receiver "front-end." The fleet got this radar, built by GE as the SC-1 or SK, and by RCA as the SA, able to detect aircraft at 150 miles range.[11]

The Laboratory also addressed the problems of radar-guided gun-laying (fire-control radar) and radar search systems for aboard patrol bomber aircraft, to combat the submarine menace. Being limited in staff, though, NRL management decided to persuade Bell Labs (and the affiliated Western Electric Organization) to undertake the development of fire-control radar, with NRL guidance. The result was the CXAS 700-MHz radar, which evolved quickly

[10]The last model of the XAR had a transmitter by Leo Young, using 12 of the Eimac tubes in a ring oscillator, producing one million watts of pulse power.

[11] Gebhard,L.A., *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratory*, pp 183ff, USGPO, 1979.

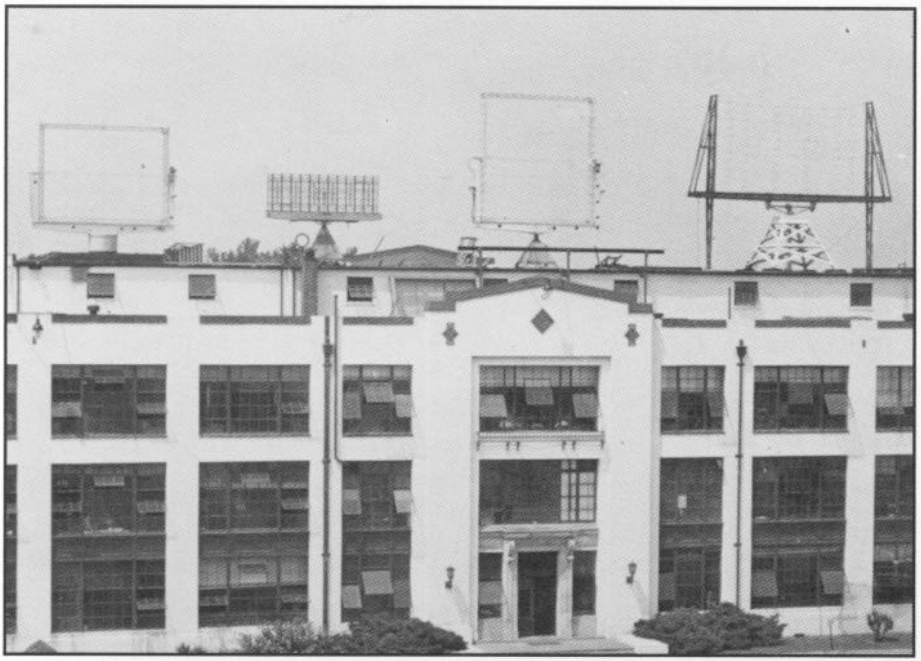

Figure 7. Antennas for experimental radars mounted on roof of NRL main building, 1939. Antennas are, left to right, type SK, type SC, shipboard version of XAF, and prototype XAF. None of these antennas has Identification of Friend or Foe (IFF) dipoles attached, which were usually above the main antenna elements. Compare this prototype SK antenna (used to search for enemy aircraft) with that of the later version by GE, the SK-2, a parabolic reflector antenna shown in Figure 9. (Photo courtesy estate of Leo C. Young.)

into the FA, FB, FC, and FD systems, the last named being able to lock a gun onto an aircraft flight in azimuth, elevation, and range. The first FD radars went on battleships and the new anti-aircraft cruisers *USS San Juan* and *USS Juneau* being built at Quincy in early 1942. These efforts were given a tremendous moral (and technological) boost by the technical exchange with Britain, to be described later, which took place in September 1940. The fleet would enter the second world war, therefore, with the SC, SK, and CXAM search radars for aboard ships, the FA and FD fire control radars, and the ASB airborne anti-shipping (and anti-submarine) radar.

During the same period, from 1934 to 1940, the Signal Corps,[12],[13] with Navy cooperation,[14] also developed and fielded three operational radars able

[12]Terrett, Dulany, *The Signal Corps: The Emergency*, pp 121ff, one of the *US Army in World War II* series, USGPO, 1956.

[13]Colton, Roger B., "Radar in the United States Army", *Proc IRE*, pp740ff, Institute of Radio Engineers, Nov. 1945.

[14]ibid., also Gebhard, *op cit.*, p195.

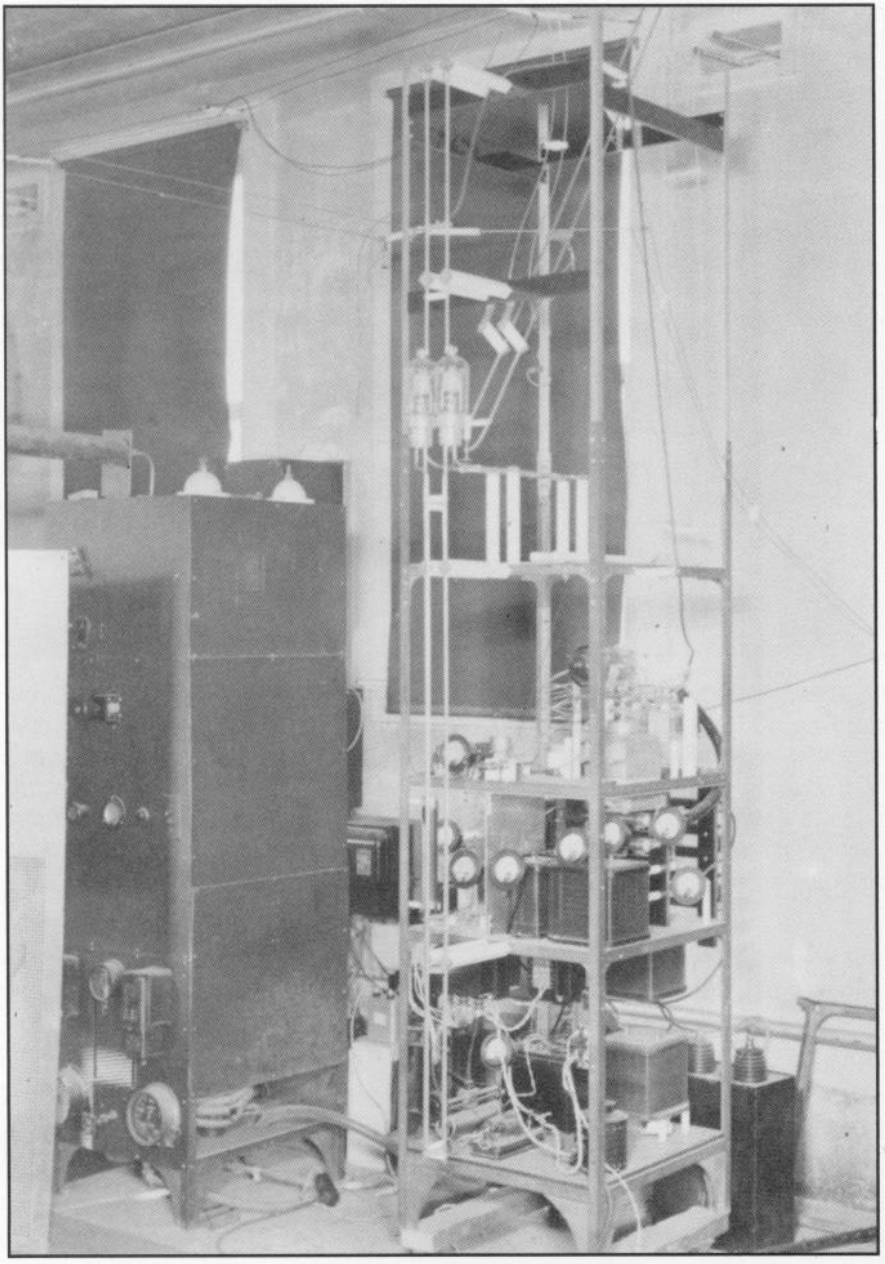

Figure 8. Push-pull transmission-line power oscillator for first XAF radar, built by Leo Young, NRL, 1936. Most of the other circuitry is for producing powerful d-c pulses to feed to the tubes' anodes. NRL utilized the services of several graduate and undergraduate students from local universities in the development of successful pulse-forming circuits for radars during the period immediately before the war. Tubes are experimental Raytheon triodes.
(Photo courtesy estate of Leo C. Young.)

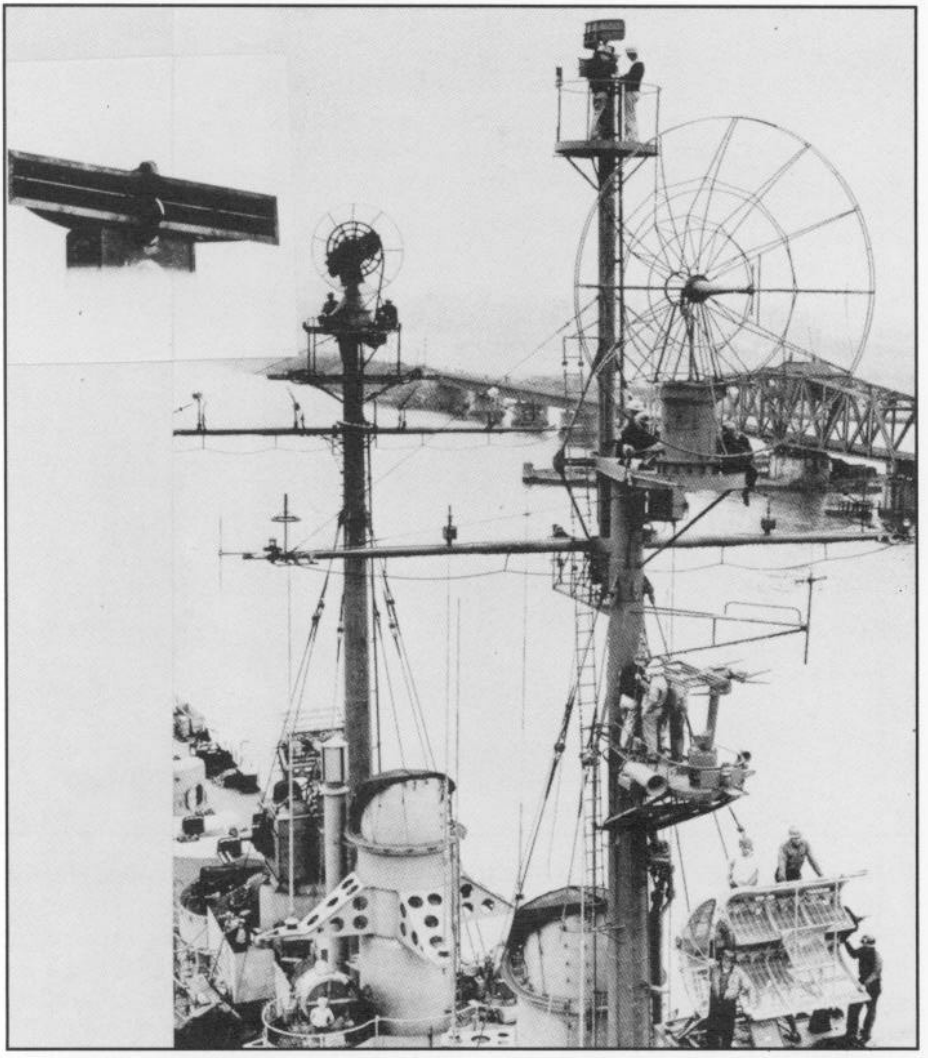

Figure 9. *USS Juneau* (anti-aircraft cruiser) in early 1942, being outfitted with radars after launching, but before its first patrol to the Pacific, at Quincy, MA. The huge parabolic reflector antenna is for the SK-2 radar, made by GE. Above it, on the foremast top, is the SG flat parabolic surface search radar, the first anywhere to use a PPI scope to give map-like plots of echoes' positions. The SG was our first surface-borne radar made from 10-cm magnetrons made to Tizard's sample's specifications, and the first ever radar made by Raytheon. The first four such radars went on the *Juneau*, the sister ship *San Juan*, the cruiser *Augusta*, and the carrier *Saratoga*. The SG was relished by fleet commanders in the Pacific, even though it was sometimes installed with too much waveguide between the antenna and receiver, resulting in signal losses which could be disastrous. The British had also started a shipborne 10-cm search radar, the Type 271, which used a "double-cheese" antenna, such as that shown in the inset. (Photo from GE Company archives.)

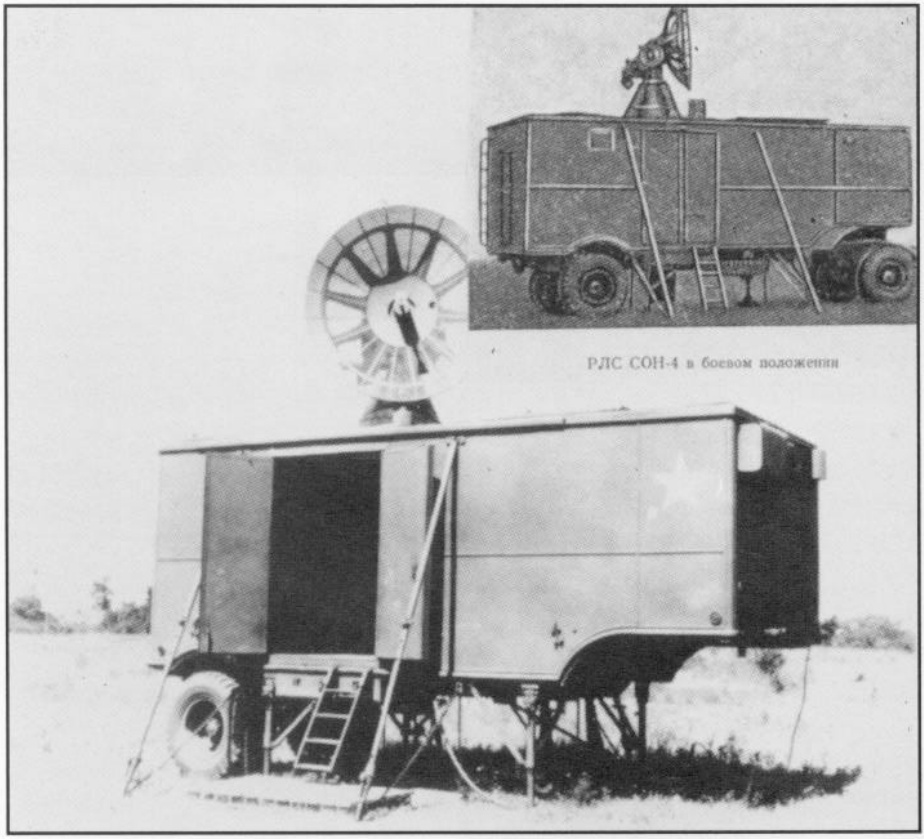

Figure 10. Signal Corps' SCR-584 10-cm wavelength radar, developed by the Radiation Lab and the Signal Corps. This radar was specifically requested by Churchill to combat the V-1 missiles. It achieved growing success in directing 90-mm flak guns against these weapons, downing about 30% of those V-1s engaged in the beginning, when the fuzing of the flak burst was time-controlled, and about 90% a few months later, when the guns used proximity-fuzed shells. About 50 of these radars were sent to the USSR for flak directing against the *Luftwaffe*. In Russia, the radar was carefully disassembled, duplicated, and renamed model SON-4, shown in the inset. It achieved such success in antiaircraft artillery that its "engineers" were awarded the USSR State Prize. (Photos US Army Signal Corps and reference 19.)

to detect and locate aircraft at ranges up to 150 miles. This work replaced, completely, earlier work by the Signal Corps to achieve detection of aircraft by sensing the infra-red radiation from their hot engines and exhaust systems, a method which fails in cloud and fog. The Army's radar transmitter designs were straightforward push-pull triode oscillators, operating at the highest power levels at the highest frequencies thought to be possible. One of the NRL inventions given to the Signal Corps in a 1939 technical exchange, however, provided a boost to all that. It was the ring oscillator, the simplest version of which used four tubes, in which each pair of tubes was in push-pull

configuration, and then one pair was in push-pull with the other. This doubled the power available from one pair, with no sacrifice in upper frequency limit. One of the radars made with the ring oscillator, the SCR-270, was in place on Oahu when the Japanese attacked, on 7 December, 1941. While it detected and located the incoming aircraft, it was inadequately integrated into the Hawaii defense network (translation: it was scorned by the military commanders), and did not effectively warn of the attack.

The Army Signal Corps felt left out of the critical wartime decision-making process in the rapidly-evolving radar field, since the Army Air Corps established direct liaison with the British, with the new Radiation Laboratory, with the Navy, and with contractors, for aircraft-borne radars, always perceived to be the last word in radar. In this way, it would be the Navy's ASG and ASD airborne radars which would be adopted directly by the Air Corps as the AN/APS-2 and AN/APS-3, respectively. By exploiting any technological left-overs they could glean in the many interservice meetings on radar, though, the Signal Corps managed to put together probably the finest heavy microwave radar of the war, the SCR-584.

In the field of research into making radar into a true "night-vision" instrument, allowing imaging, or visualization of the disposition of echoes elicited by the radar transmitter, the primary thrusts were in reducing the radar operating wavelength (tending toward that of visible light) and in display technologies. As we will describe later in this paper, A. W. Hull's invention of the magnetron, supplemented by the research by Arthur L. Samuel, paved the way to a workable device which could produce radar wavelengths of 3 centimeters or less, by 1937. At NRL, the invention of the plan-position-indicator (PPI) type of cathode-ray-tube (CRT) display allowed the imaging of radar echoes in a completely natural mapping format. The combination allowed the development of high-resolution, mapping radars in which ordinary officers could assess the battle situation at a glance at the CRT display.

But the primary advances in American radar technology during the second world war were enabled by the pooling of expertise from all the services, contractors, universities, and all the allied countries, which allowed relatively free exchanges of ideas among American, British, Australian, Canadian, and French workers in the field. This interchange of experience produced the first high-power, mass-produced magnetrons, the first radars to allow blind bombing, or to be able to "see" submarines by means of echoes of their *schnorkel* heads, alone, and a formidable array of anti-radar devices (electronic countermeasures, or ECM), able to thwart the performance of German and Japanese radar systems, when they made their appearances in the war.

Germany:

But antedating the earliest NRL efforts was that of Germany's Christian Hülsmeyer,[15] of Cologne. After the death of a close friend in a 1902 collision between two ships in a fog, Hülsmeyer sought ways of ships sensing each others' presence in such weather, and at night. Upon studying Hertz's laboratory demonstrations of electromagnetic waves, he put a battery-powered spark transmitter and a Branly coherer-equipped receiver on Cologne's *Hohenzollernbrücke*, a railway bridge over the Rhine, to see if he could duplicate Hertz's experiment with reflections of Hertzian waves. His method was elegant, even by today's standards.

He reasoned that there were actually two pathways along which signals could get from his transmitter to his receiver: one path was directly from transmitting dipole antenna to receiving dipole, just a hundred yards down the bridge; the second was from the transmitting dipole down to the water surface, then bouncing back up to the receiving dipole. He thought it would be possible to adjust the positions of the two dipole antennas until the two paths differed in length by exactly an odd number of half-wavelengths, at which point the receiver should sense a minimum signal level. (In this condition, the signals traversing the two paths cancel each other.) Then, perhaps, the passage of a ship through one of the paths (the one that bounced from the river surface) would upset this delicate signal balance, markedly increasing the signal level received, and enabling the ship's detection.

By moving and carefully rotating the receiving dipole a little, he actually got the two paths to cancel each other, and the decoherer he used in the receiver suddenly quit ringing its little doorbell. To make the receiver again receive a strong signal from the nearby transmitter, all he had to do was place a large sheet of metal either between the antennas, about 30 or 40 yards from either dipole, or under either antenna, blocking to some extent its ability to either transmit to, or receive from, the river surface. He could make the bell ring by passing the metal sheet across either path.

Sure enough, when a ship approached the bridge, the bell began to ring, only to quit again when the ship had passed completely clear of the bridge. The action was repeated again and again as excursion boats and freighters passed the bridge, going up and down the Rhine. Both Hülsmeyer and the German Navy (*Kriegsmarine*) were quite impressed, but the military did not get any further involved. They felt fog horns were more efficient. Based on the size of his dipoles, recorded as being about a rod each in length, he operated at about 30

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[15]Lyon, Ed, *USAF SATAF Newsletter*, SRI International, Arlington, VA, 1988.

MHz. Late in 1904, he obtained a British patent for "a radio wave projecting and receiving apparatus which could detect reflections from metallic bodies, like ships and trains." He called his apparatus a *telemobiloscop*, and demonstrated it several times in Cologne that year. Of course, the range over which such a radar could detect ships was very short, as only coherer detectors were then available.

Then, during World War I, two Germans, Dominik and Scherl, demonstrated another radar device, which would detect the presence of metallic objects, just like the *telemobiloscop*. This time (in 1916) the *Kriegsmarine* was interested, but when the inventor estimated that it would take six months to build a working model aboard ship, his caution doomed the project. The Navy felt the war would be over before six months' passing. Finally, in 1933, Kühnhold, a German Navy scientist, revived the Dominik/Scherl idea, and built a crude radar to detect ships. His work got the attention of the Gema Company, and by 1936, their scientists brought some of their recent research to the attention of the military, but again only the *Kriegsmarine* liked the idea (since they thought it was their own idea, at that), and they contracted with Gema for the development of two radar systems, *Freya,* operating at 125 MHz, and *Seetakt,*[16] operating at 375 MHz. To the rest of the military, radar seemed to be a defensive tool, and at that time the very thought of a defensive posture was anathema to the very highest levels of German leadership.

The Germans would not be able to conduct earnest research into microwaves[17] or into imaging display devices for their radar systems because of bureaucratic restrictions (such as the one-year-rule, to be discussed later) and because of the pressure of the war in which they were immersed. Radar engineers in Germany were rudely thrust into the field of microwaves upon the German recovery of a crashed RAF Short Stirling bomber carrying a 10-centimeter target-mapping radar near Rotterdam in early 1943, and from then it was a game of "catch-up."

The Soviet Union:

In 1934, Alexandr Alexeyevich Chernyshev, of Leningrad, realized that the research on detecting and tracking airplanes by using acoustic collectors was hopeless because of the growing speeds of aircraft, and he also realized that detecting the infrared heat emitted from a target was a difficult task in all but

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[16]US War Department, *Directory of German Radar Equipment*, TM E 11-219, USGPO, 1945.
[17]Even though *Electronics* magazine (September, 1935) reported Telefunken to have a 10-centimeter wavelength aircraft locating "radar", able to find aircraft in fog.

clear weather.[18] He assigned the job of developing an electromagnetic detection scheme to B. K. Shembel.[19] Chernyshev and Shembel calculated that it would have to be radio-wave reflection that they would receive, not inherent noise radiation from the aircraft, as Captain Edwin Howard Armstrong had done in World War I. Meanwhile, Y. K. Korovin, working with the Soviet Army antiaircraft artillery forces (*UPVO strany*) had already started a competing project for the aiming of flak guns based on aircraft-radio reflections. Korovin pressed for frequencies in the several-hundred MHz region, while Chernyshev felt that they could not hope to achieve reasonable transmitted power levels above 60 MHz. Lobanov, considered the Soviet "Grand Wizard" of radar, and who professed not to take sides,[20] really favored the lower frequency approach, mainly because of the lower risk factor involved. Both frequency areas were pursued for two years, and, after the second world war, the Korovin team claimed that in 1938 they had developed, on their own, a multicavity magnetron for the production of 10- centimeter radar waves. (Strangely, the cavity-magnetron-equipped US. Army Signal Corps SCR-584 10-cm radars given to the Soviets in Lend Lease were warmly welcomed in 1944, and were bitterly competed-for throughout the Soviet Union, remaining in use at least through the early 1980s. They, and not Korovin's magnetron, became the design basis for nearly all Soviet radars since then.)

The Soviet program to put an airborne intercept (AI) radar in a fighter plane to combat attacking bombers got a late start, and the first effort was to use a klystron-powered 10-centimeter wavelength set, called *Gneys-1*, in early 1941. It was seriously underpowered, and in attempts to boost more from the NII-9 klystron, the test team succeeded in using up all the available supply of tubes. The war was now on, and no more klystrons were authorized for manufacture, so the engineers turned to more conventional designs, centered on 200 MHz (1.5-meter wavelengths), and the *Gneys-2*. Evacuation of the work to the east, upon Germany's invasion, slowed the work, and it would not be until the end of 1944 that as many as 230 such radars were produced.[21]

After the war, Chernyshev, too, saw his own early work in a new light, as he is reported, in Shembel's book,[22] to claim to have detected and tracked aircraft at 40-km ranges with his 60-100 MHz radar. Chernyshev's radar was

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[18]The Soviets had an acoustic airplane detector, model ZT-2, and an infrared detector, made from a searchlight housing and reflector, model TU-1.

[19]Shembel, B. K., *U Istokov Radiolokatsii V SSSR* , preface, Moscow, Sovetskoe Radio, 1977.

[20]Lobanov, Mikhail Mikhaylovich, *The Development of Soviet Radar*, Voyennoye Izdatel'stvo, 1982.

[21]*ibid.*

[22]Shembel, B.K., *op cit*, pp7-22.

called Rapid, and after 1934 he had to "steal" project funds from other assignments to keep up the experiments, before the whole program died. Somehow, though, the military did not see fit to fund either his or Korovin's project after 1937-38. The military seemed uncertain as to whether a flak-directing system was worthwhile, or whether it helped to know from whence approaching aircraft came.

Japan:

The background of Japan's electronics industry in support of military objectives prior to the second world war had been ferreted out of what was left of the country's military records by American intelligence officers in the occupation period, from 1945 to 1948, and from equipment and papers captured in the island invasions of the Pacific war. These records painted a dismal picture of Japan's research into radar, and indicated that they copied, freely, German and captured Allied designs, and developed very few systems themselves.[23] The wrecked Japanese radar recovered on Guadalcanal by the Navy and returned to NRL for analysis, for example, was a rough copy of the American SCR-270. Recently, however, Japanese scientists who were involved in the development during the war have written of their experiences, and we have learned some interesting things of those times.

Shigeru Nakajima, a scientist during the 1930s with Japan Radio Company, recently wrote an article summarizing what he knew of Japanese radar development in that period, in *The Radioscientist*.[24] Nakajima writes that the Japanese scientists had to endure extensive criticism from the military and civilian science organizations alleging that the research was frivolous and without useful application. He notes that a scientist named Kinjiro Okabe, of Tohoku University pursued work on ultra-high frequency signal generators, using Hull-type magnetrons and Barkhausen-Kurz tubes in 1932. This much was acknowledged by the American intelligence officers who investigated Japan's technology after the war.

But, Nakajima's article also discloses a bolder historical technological image emerging: the Japanese currently consider Okabe to be the **inventor** (in 1925) of the split-anode magnetron, despite his patent issuing 9 years after Hull's. Okabe proposed a magnetron-powered radar to detect ships, but nothing was funded by the Japanese military until 1937-38, when the Japanese Navy sponsored his development of the "mandarin-anode" magnetron, of the multi-cavity type. Okabe credits invention of the multicavity-anode magnetron

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[23]See also Price, Alfred, *The History of US. Electronic Warfare*, pp289ff, The Association of Old Crows, 1984.

[24]Nakajima, S., *The Radioscientist*, Vol. 3, No. 2, pp. 33ff, International Union of Radio Science (URSI).

to A. L. Samuel, an American, in a book[25] written by Okabe in 1937. Photographs of the magnetron claimed in Nakajima's paper to be Okabe's 1938 model show it to have been virtually identical with the one first brought to America by Britain's Tizard, in 1940. It would be astounding if these two developments were truly independent.

But all of the bits and pieces of information that Japan's military intelligence people kept gleaning from the US. and Britain throughout the war, and in the few years just before hostilities began, were poorly assimilated, and kept her technologically off-balance. As a result, Japanese scientists in the field lacked a strategy for any stable development program, while the sheer military support for any radar development at all remained ephemeral. For example, on an early (in 1941) visit to Germany, Japanese observers learned from German intelligence that the British were apparently working on their 12-meter-wavelength (Chain Home) and their 60-centimeter-wavelength (upgraded ASV) radars. On their return to Japan, they changed the direction of radar development to mirror that of the British. Capture, later, of an American plane with a 515-MHz (60-cm wavelength) version (the ASB-5) of the British 1.5-meter ASV radar confirmed this decision as being "right." Later they were invited to copy the German *Würzburg* radar, also operating at nearly the same frequency. This further confirmed that any work that might have been underway on 10-cm and 3-cm magnetron research was probably "wrong." The Japanese Navy had, at the time, been painstakingly developing a 10-cm wavelength radar for use aboard ship,[26] and several trials had been run with these radars on submarines, as well. But the project did not receive high priority, as it seemed out of step with what other nations were perceived to be doing.

Even though the Japanese fleet officers understood the value of radar, the Japanese Naval high command failed to appreciate it, and they had only to look at the outcome of the raid by Admiral Mikawa's radarless Eighth Fleet on the radar-equipped allied fleet guarding the invasion forces at Guadalcanal, for confirmation of their prejudice. Mikawa's was a lightning plunge through the Solomons Slot at night,[27] which resulted in catching the Americans fully by

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[25]Okabe, Kinjiro, *Magnetron Oscillations of Ultra-Short Wavelengths*, Shokendo Publishers, Osaka, 1937. Samuel, of Bell Labs, is better known for his late-1930s work on the radar duplexer, a device which allows radar transmitter and receiver to share a common antenna, and for his 1946 invention of the first computer which could play checkers against a human. Samuel did, however, invent many UHF oscillator tube configurations, including the multi-cavity anode magnetron, U. S. Patent No. 2,063,342 (8 Dec 1936).

[26]The Mark II Model 2, built in a total quantity of 400 from 1942 to 1945.

[27]US naval strategists agree that the Japanese Navy trained thoroughly for night engagement, selecting gun directors and lookouts specifically for the best night vision. Their naval guns used flashless powder, which made black smoke, while US guns then used smokeless powder, producing considerable flash, which ruined night vision immediately after the first exchange in battle. Thus, we relied on radar, and when it failed to detect Mikawa's column (the US radar picket involved used the CXAM which was plagued by island echoes which masked Mikawa's ships' echoes), the Japanese had the advantage of surprise.

surprise, and the sinking of the cruisers *Canberra, Astoria, Quincy*, and *Vincennes*, with no losses on the Japanese side. The type of radar on the American picket ships was the 1.5-meter wavelength CXAM, which had difficulty discerning ships from small islands in the background, allowing Mikawa's fleet to infiltrate the allied flotilla. A few days later, in the second battle of the eastern Solomons, 40-centimeter-wavelength type FD fire-control radars on the *USS San Juan*, an antiaircraft cruiser, enabled such concentrated and accurate flak to be pitted against the Japanese carrier bombers that the *USS Enterprise*, the last American carrier operating in the Pacific at that moment, was saved.

The Japanese Naval high command got their wake-up call in the Battle of the Coral Sea, when their ships began getting shelled at nighttime by large guns from American ships. The Japanese units were found by the XAR series of radars, and were fired on through magnetron-powered 10-centimeter wavelength SG radar direction and precision ranging. One additional factor diverted Japanese attention from the concept of early development of a multicavity-magnetron-powered radar; the notion of producing a powerful Death Ray, able to damage aircraft in flight, was taken seriously in Japan,[28] and giant magnetrons were developed to conduct research in this area, at the expense of radar development.

So, although Japan had a complete radar design fielded by 1939, and although some now claim they had the magnetron technology required to produce truly fine-resolution-imaging radar systems, their Army's appreciation of radar was not decisive, and the scientists only acquired full military support for a radar in 1942, when they fielded the Taichi-6 and -7 radars, almost identical to the American SCR-270 and -271 systems captured in the Philippines.

Great Britain:

In 1935, A.P. Rowe, "Skip" Wilkins, and Robert Watson-Watt successfully detected the flight of an approaching aircraft, using a radar made up of the 5XX international broadcast station at Daventry (England) and their receiver in a van near Daventry. They promoted this crude radar into a complete system of HF (wavelengths of 12 to 20 meters) radars stretching halfway around the British Isles, the Chain Home system. By 1939, they had developed a 60-cm-wavelength airborne offensive radar called the ASV, critical to the Battle of the Atlantic.

In 1939, University of Birmingham scientists discovered that GE's magnetron, of 1916, could be made in a multicavity style (much like A.L.

[28]Nakajima, S., op cit., p34.

Samuel's patented multicavity-anode magnetron of 1936), and thereby have its power-handling capacity greatly increased, as an oscillator. They built a magnetron-powered radar at 10-cm wavelength, the model H_2S, able to be fitted into interceptor aircraft, for locating and shooting at other aircraft. And, by sharing their developments with their principal allies, together they were able to afford the luxury of developing and mass producing both radar and counter-radar technologies, both of which were decisive in the war's outcome.

The Race

Every one of the involved nations shared a common set of characteristics: each developed radar in complete secrecy, and each had a navy which was desperately trying to develop a defensive radar system which might help preserve their ships from the dreaded bomber aircraft. Billy Mitchell's demonstration clinched it. But as nations, each, save one, was ambivalent about what utility radar would have, militarily.

Only Great Britain, with a vulnerable geography, *vis-a-vis* their traditional rivals, and with a ship-like insular physiography, saw the utility of radar in exactly the same way as their navy, and the other navies, saw it. The British, as a nation, seemed to be unique in having a well-focused idea of **what they wanted radar for,** namely, to help in the defense against attacking aircraft. Most other nations who examined radar as a military weapon considered it primarily as a "blind targeting," or offensive, asset, or they were ambivalent about its purpose, switching from offensive to defensive applications.

Until 1941, the Germans had largely ignored radar because they originally saw it as defensive, not offensive. Then, by the time they had mastered offensive applications, they were being counterattacked, and desperately needed defensive radar help. Germany's *Seetakt* radars, designed for defensive use aboard ships, were modified to be used to aid in the attack of British shipping in the Channel, and later German radar systems were designed to augment, and replace, the *Knickebein* system for bomber guidance over England, and to watch for the British fleet. A low-priority use was to watch, defensively, for threatening aircraft flights. The German efforts were significantly dissipated by the Goering order to keep all research projects aimed at short-term tactics, and by the high command's ambivalence between defense and offense.

Even the US. Army showed a lack of appreciation for the defensive value of early-warning radar, and the excellent lead time they had before they would desperately need such defensive "vision." They even wasted nearly a year, in 1940-41, in trying to modify the SCR-268 and SCR-270, which were

their first effective ground-based early-warning (against aircraft attack) radars, for use aboard Air Corps aircraft, so as to improve the score in offensive anti-shipping attacks. On the other hand the US. Navy's (RCA) CXAM radar went aboard ship promptly in 1939, with no fanfare and no hesitation, in a strictly defensive mission. Later, the SG shipboard radar, with its map-like (PPI) display screen, made radar appreciated, even by admirals.

The Russian and Japanese military forces didn't take radar seriously until the war was upon them, and they never got their systems working satisfactorily. Hurriedly designed flak-directing radar was extensively used against LeMay's B-29 Superforts as they destroyed Japanese cities, but massive use of electronic countermeasures by the bombers effectively took these radars out of the picture.

The British faced a decidedly different problem: they had become convinced that unless something decisive could be done about interception of long-range bomber aircraft, any war with the continental nations would bring either capitulation of Britain, or its total annihilation, and with either, the end of the democratic free world. In this respect, they thought like Navy people. They discovered that radar could just possibly bring about this decisive interception process.

So, with the development of radar underway in at least five different countries (France also has claimed to have been developing such a system, making it six), all in relative secrecy, there definitely was a race going on, but it seems that only the British realized that it was an out-and-out race. Everyone else was jogging.

But the British radar, sufficiently developed to enable the RAF to anticipate the location of virtually every German bomber attack during the Battle of Britain, almost never came into being.

The Death Ray

The Great Depression, which really took firm hold in 1930, was felt round the world. Here Herbert Hoover took the rap, and he was summarily replaced by FDR in the 1932 elections. In England, the government of Prime Minister Stanley Baldwin was blamed and his Conservatives fell, being replaced by a Labor government headed by Ramsey MacDonald. Since Labor couldn't sweep out all the opposition, a coalition government was formed in which Baldwin stayed on as Lord President of Great Britain. At this time Churchill was head of the Admiralty.

In a speech before Parliament in 1932, the Lord President spoke of the danger that Britain faced from the continent. In virtually all the countries of

continental Europe the post-World War I political unrest, coupled with the depression, had created an atmosphere of revolution. Now, the petty arguments among the many royals on the continent, which had not been resolved one whit by the War, festered anew, with most people blaming their economic hardship on foreigners. A new war was felt to be inevitable. In his speech, Baldwin made the statement that in any war of the future **"the bomber will always get through...."** This alarmed the Ministry of Defence, because in those times of shortfalls in budgets, their air defenses, if perceived to be hopeless, could easily fall even lower on the priority scale. Thinking that the best defense against budget cuts might be a strong offense, the Defence establishment took several measures to challenge the Lord President's claim.

The first came in 1934, when Professor Lindemann, the Prime Minister's scientific advisor, wrote in the London Times that it was totally unacceptable to acquiesce to such a concept. Indeed, if "...the bomber will always get through..." meant that the only answer to a potential attacking bomber fleet was the mirror-image threat of massive retaliation, then, according to Lindemann, the temptation for a country to "jump the gun" and unleash a devastating sneak preemptory attack would be unbearably strong, and the world would become unstable as a result. He insisted that the scientific community be funded to find a way to stop the bomber. That very year his claim was vindicated.

That summer a military exercise was planned, in which the latest defenses against an attack by unannounced bomber aircraft were to be tested. The interceptors and anti-aircraft guns were readied, and massive acoustic aircraft detection systems were emplaced. As the expectancy of the mock raid mounted, casual sources of noise which paralyzed the acoustic systems were hurriedly located and quieted. Milkmen making their morning rounds were forced to stop, absolutely still, and try to keep their horses from restless activity. All these artificial precautions were horrifying to objective scientist-onlookers, who wondered just how you could expect to keep the countryside deathly quiet if a real air attack were imminent. But they also knew that a greater problem with acoustic detection was that the speed of sound waves is not markedly higher than that of the aircraft they were detecting, and so the warning time afforded by the system amounted to but a few minutes. Acoustic detectors told you, at best, where the aircraft had once been, not where they were, or where they were going.

The exercise was a disaster for air defense, for they only slightly blunted the mock attack. The RAF was beginning to believe that the Lord President was right: the answer to enemy bombers was more bombers of their own. This, apparently, was the birth of the concept of mutual assured destruction (MAD), a concept which would be reborn after 1946, and which

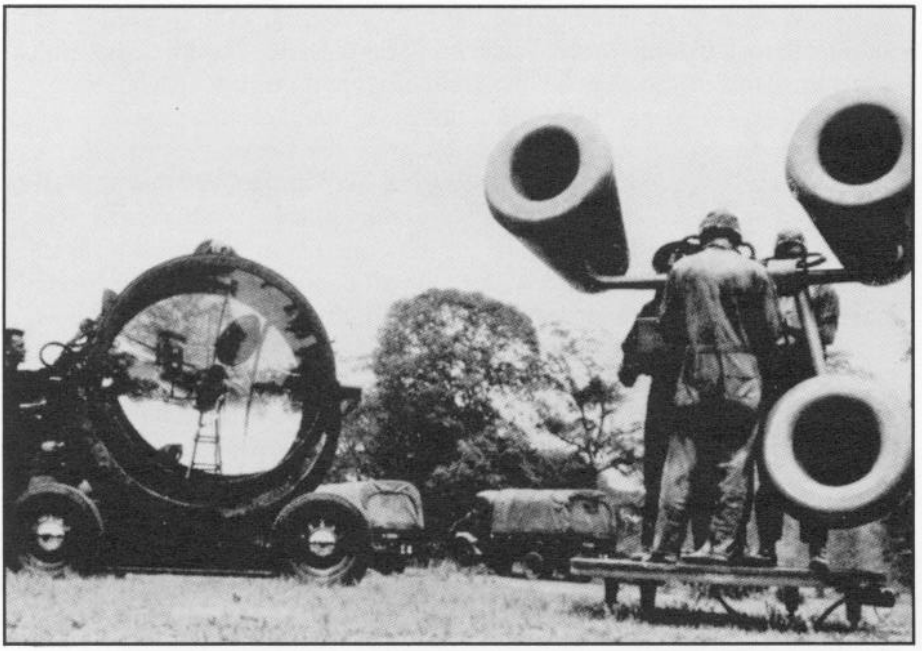

Figure 11. Acoustic aircraft detectors of 1935, used until 1941. Searchlight on left was converted to an infrared detector, used in conjunction with an acoustic detector, and equally as unsuccessful. (Photo from GE archives.)

dominated international strategic thought during the ensuing 45 years of Cold War.

The second RAF reaction to Baldwin came from people who might have seen one too many "Buck Rogers" movies or comic strips. In these old sci-fi thrillers, Buck always won the day for the good guys by using his "Astro-Ray" gun, which had the power to stun, or wipe out, anything in its ray-path.

In 1934, in apparent seriousness, the Air Ministry Director of Scientific Research, Dr. H. E. Wimperis, had asked his staff, in the person of Robert Watson-Watt, if a "Death Ray" could be devised which could knock out an aircraft in flight, or at least incapacitate its crew. The idea came from the highest circles in the government, and began as a result of a memo to the Prime Minister from A. P. Rowe, Wimperis' assistant. In it, he explained that the idea of belligerents resorting to unopposed bombing of each other was hideous, and that the government should pay science to step in with some sort of solution, quickly. The P.M. was sympathetic, consulted with his science advisor, Lindemann, who thought of several outlandish schemes for destroying attacking bombers and rippled a suggestion down to Wimperis to "do something."

Watson-Watt asked one of the staff scientists, "Skip" Wilkins, to run through the calculations to see if such a ray was feasible. Together, they quickly determined that there was no known technology at the time which could provide sufficient power to harm the pilot, let alone damage the airplane. While computing how much electromagnetic energy the airplane's structure would receive from the "ray" emitter on the ground, Wilkins realized that most of the energy would be re-radiated from the plane. This was simple electromagnetic wave reflection. In his conclusion, reported to Watson-Watt, Wilkins remarked that, with the most powerful "ray" (interpreted to mean "short-wave") transmitter he could think of, the aircraft would certainly reflect enough of the transmitted signal that the echo alone could be detected at a great distance, probably as great as 100 miles, allowing, perhaps, the interception of the aircraft by more conventional means. With the speed of radio waves being so very high, relative to the old acoustic detector methods, this would afford at least 20 to 30 minutes' warning time for a bomber attack.

Watson-Watt included this statement in his summary memorandum back to Wimperis, explaining to his boss that the Death Ray couldn't be made to work, but that they thought they could utilize a radio signal reflection-finding (much later to be called "radar") network to locate attacking aircraft long before they reached their targets, enabling the RAF to place interceptor aircraft in just the right places at just the right times to spoil the attack. The memo went on to explain that the "radar" did not require that the enemy aircraft create radio signals; the network stations would be receiving radio echoes of the aircraft, not self-radiated noise as had been thought a possible early-warning scheme in World War I by Armstrong. Wimperis ordered an immediate test of the reflection-detection principle.

Wilkins calculated that a typical bomber-sized airplane would be quite reflective (and hence, would yield a strong echo signal) if the transmissions striking it were at just such a radio frequency that the aircraft major dimensions (wingspan or fuselage length) matched the radio wavelength. Here, he was on the right track, or at least nearly right; the highest reflectivity occurs when the aircraft dimensions (wingspan, or fuselage length) are **one-half** the radio wavelength. As it turned out, the most convenient feasibility test Wilkins and Watson-Watt could think of called for the use of a shortwave broadcast transmitter, such as the powerful (20 Kw) 5XX station at nearby Daventry, operating at 49-meters wavelength, as the "illuminator." This would create a maximum echo signal from any aircraft having an 80-foot span, which was the approximate size of the German Heinkel 111 bomber, and of the ancient Handley-Page bomber which was to fly a test against the rudimentary radar. The echo-receiving equipment was set up in a small van near Daventry. It comprised a short-wave receiver, a heterodyne oscillator, and a strip chart recorder to

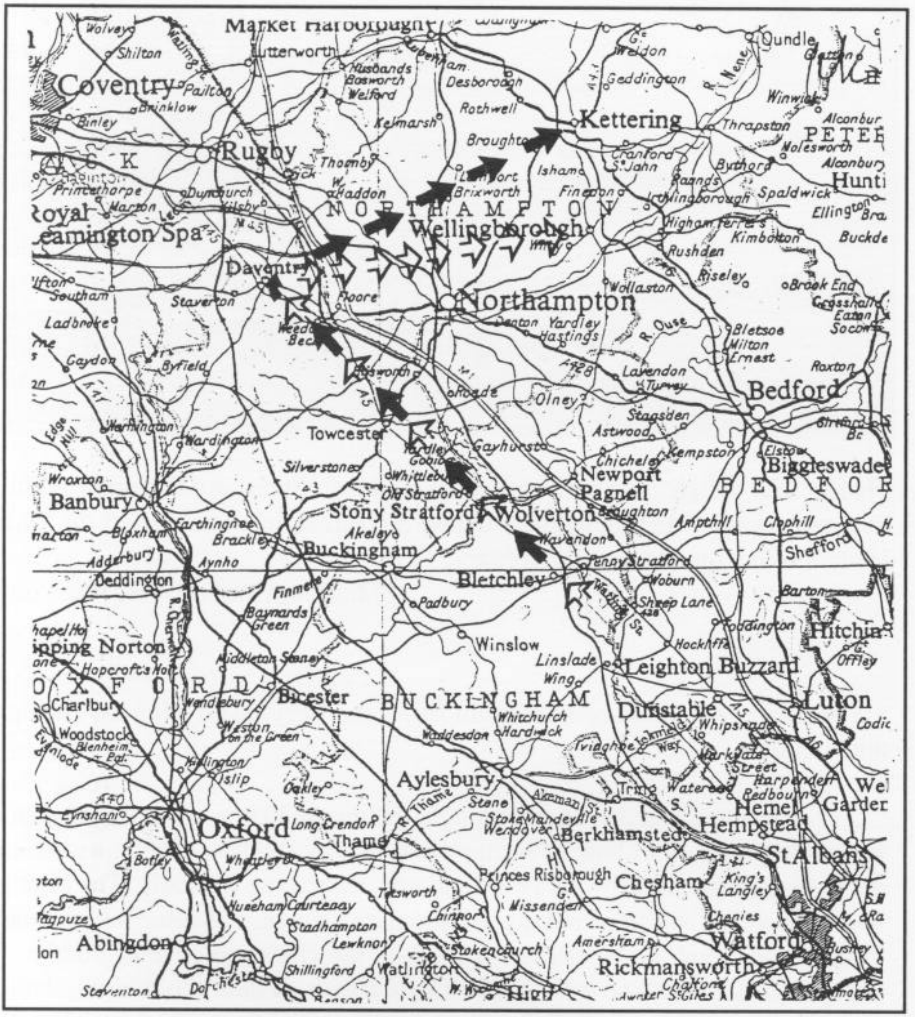

Figure 12. Map of Daventry surroundings, showing route planned, and that taken, by test aircraft in first field experiment in the development of Chain Home. Aircraft radial velocity from the receiving van east of Daventry could be determined from the Daventry signal fading rate, allowing Watson-Watt to suspect that the plane went off-course to Kettering, rather than to Wellingborough. (Original map from London Times.)

ink out the heterodyne tone from the receiver. On a cold February 26th, in 1935, the tests began, with A. P. Rowe as the only impartial witness[29]. The Handley-Page bomber was to approach Daventry at 2000 feet altitude, arriving at 10:30 in the morning. Over Daventry, the pilot was to fire a Very flare, turn for Wellingborough, about 28 miles away, and after reaching that town, return

[29]Rowe, A. P., *One Story of Radar*, p.8, Cambridge UniversityPress, 1948.

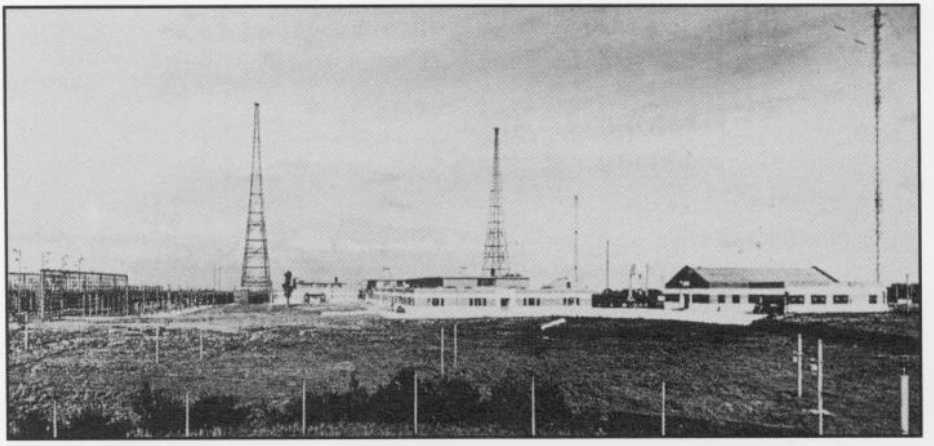

Figure 13. High powered shortwave transmitters at Daventry. These transmitters provided the signals whose aircraft reflections started the Chain Home project on its way, in February, 1935.

(Photo from *Radio World* magazine.)

via an exact reciprocal course, again firing the Very pistol over the Daventry antenna farm.

During the actual flight, though, the winds aloft were stronger than on the ground, and some cloud cover appeared, especially east of Daventry, making navigation, crude then by today's standards, even more difficult. The pilot got lost for a while, just after making his turn over Daventry. Seeing no landmarks through the cloud, he headed for a break in the cloud cover, and found a city straight ahead, which he took for Wellingborough. It didn't look right, though, and after his turn-around, he figured he had headed for Kettering rather than Wellingborough, eight miles off course. Pilots rarely brag about getting lost, and so Squadron Leader Blucke, the pilot of this particular bomber, kept his mouth shut, fired the Very pistol upon finding Daventry again, and headed for base.

In the receiving van, Watson-Watt, Wilkins, and Rowe watched the Daventry signals fading up and down as the bomber flew over, watched the signal fading smooth out as the plane disappeared, and then saw them dance up and down again as the plane returned. As soon as the plane had retreated, finally, out of range, on its way home, they packed up the strip-chart recordings and dashed off to London to reduce the data. They were certain that they saw signal fading caused by airplane reflections affecting the received signals, and they were very optimistic about this new technique which would someday be given the American name, "radar."

The data showed a curious thing, which puzzled both Wilkins and Rowe: provided the plane flew at a constant airspeed, which was one of the requirements, the angle through which the plane had turned should have been able to be calculated from the data, and when this was done, it did not match that required to fly to Wellingborough at all. They checked and rechecked the data and the pilot's log. They concluded that perhaps the signal fading had nothing to do with the plane, after all, and that it was just chance fluctuation, caused by ionospheric vagaries. They went to Watson-Watt, to tell him the disappointing news.

Watson-Watt would have none of it. He questioned Blucke, the pilot, again, who confessed that they probably had flown to Kettering instead of Wellingborough. This fit the data nicely, and now all three scientists smiled. Their report to Wimperis stunned the old man, who didn't expect either the Death Ray or the airplane reflections idea to work, and he said, simply, "Well, now we've got our work cut out for us, don't we?"

The decision was made to cover the southern and eastern seacoasts of Britain with radio transmitter/receiver stations, and to link them all with a master filter center. Here, the target echoes would be sorted out, so that a given target aircraft would not be counted as several aircraft, just because several stations detected it. It was felt that a dense network was necessary, since the individual transmitter/receiver sets making up members of the network would have little or no direction-finding capability. This deficiency was a natural consequence of the very limited directivity of the antennas they would have to use, at the relatively low frequencies of their system, 12 or 23 MHz. Secrecy of the project was of paramount importance, and so, since the stations could **not** accurately determine the direction from which an echo was detected, they were called Radio Direction Finders, or RDF, just to confuse the uninitiated. The RDF name was thought to be especially apropos, too, because the association of the project with Watson-Watt was bound to leak out, and he had acquired some degree of prominence in short-wave direction-finder design.

The Watson-Watt method of direction finding[30] used a form of the Adcock antenna, which gave good directional results on strong signals, but on mere echoes of aircraft, not much was expected. Of course, by using several sets of stations, the direction to a common reflection could be computed, by "triangulation." The network of communications circuits linking all the RDF sites with each other and with the filter center, and it

[30]Bond, Donald S., *Radio Direction Finders*, pp109-110, McGraw-Hill, 1944.

with Fighter Command would prove, in the end, to be the key to radar success in the coming Battle of Britain. But first, the network had to be designed, and only if the technique, crudely demonstrated at Daventry, could be made to work systematically. There would have to be a major effort expended just to obtain the electronic parts required to make up such a network of radars, and some of the parts simply weren't commonplace in the radio industry in Britain.

For example, in order to display the individual RDF station's echo data to the operators, large cathode-ray tubes were needed. The first trials would have to use ordinary 3-inch and 5-inch oscilloscopes for radar displays, but the resulting operator fatigue factor turned out to be serious, and so larger tubes were desired.[31] The science of high-vacuum cathode-ray tubes[32] was still based on Braun's work in Germany, and it was not at all certain that sufficient screen resolution could be achieved with small tubes. At the time, the current German theory on these tubes called for the introduction of inert gases to pare the cathode beam down to the desired thinness, one of the requirements for achieving a high-resolution display. This called for large cathodes, which didn't last long, owing to ion bombardment. Other tricks to stretch out the display axes were tried. Stretching the time baseline by means of the already-tested German method, now called the J-Scan (in which the time base is a circular trace, and the "blips" are radial pips sticking outward or inward from the trace), didn't help much. At best, it increased the trace length from 5 inches to 12 inches, but it seriously squeezed the other dimension, usually reserved for echo amplitude.

It was at about this time that Philo Farnsworth, an American, sold to the BBC the key to producing fully electronic television centered around his new image dissector camera tube (for which he had applied for a US. patent, finally granted in July 1937). Farnsworth had been forced to sell his tube to both the Germans and the British, since he had been pre-emptorily kicked out of David Sarnoff's RCA offices, and that meant there would be no market for his TV camera anywhere in the 'states, where RCA ruled the electronics world. Sarnoff claimed already to have a better camera tube, Vladimir Zworykin's iconoscope, which was actually still two or three years away from practical production. Now, any fully electronic television system boasting an electronically-scanned, high-resolution camera tube would require the development of high-resolution cathode-ray tubes for the viewers. The Air Ministry strongly urged the BBC to promote this electronic TV system, despite strong criticism from backers of John Logie Baird's mechanical TV system, so that valve manufacturers like Mullard,

[31] At this time, the map-like plan-position-indicator (PPI) display had not yet been introduced to the British or Germans.

[32] von Ardenne, Manfred, *Cathode Ray Tubes*, pp14ff, 21,25ff,28, Pitman & Sons, London, 1939.

Tungsram, Cossor, and others, would be encouraged to finance the development of big-screen TV picture tubes, exactly the cathode ray tubes the radar people needed to have someone develop, but couldn't afford.

Chain Home is Born

Rowe, Wilkins, and Watson-Watt were given about £12,000 to build a practical demonstration model of RDF station to detect and locate distant aircraft. By this was meant that they had to test the system for overall warning time, target position accuracy, and reliability in warning of intruding aircraft. The aim was to use radar (or RDF) to direct interceptor aircraft to the right place at the right time to maximize their kill ratio against enemy planes. At the time, 1935, it was not at all certain who the enemy might someday be, and so the warning tripwire scheme had to work against France, Britain's traditional enemy, as well as Germany, whose *Reichskanzler* ranted daily about needing more *Lebensraum.* And if Germany were to emerge as the adversary of the British, the problem was to be even more serious, since Goering was building a fleet of very fast twin-engine bombers and very accurate dive bombers. The Brits couldn't hope to shoot enough of these down unless they had **both** a working RDF and some really capable interceptor aircraft, and in 1935, they had neither.

By the summer of 1936 the RDF network, called *Chain Home*, had its first station ready for trials against a fleet of mock enemy bombers. The station had been erected on the bleak, wind-swept coast at Orfordness, at great expense of human effort, as each component had to be ferried over gravelly shoals and mud. This location was chosen for security reasons: there had been an earlier wireless transmitting station there, and the new RDF site looked just like the old wireless, and wouldn't attract much attention. Early tests of the equipment were somewhat encouraging, as Wilkins detected aircraft of opportunity at ranges as great as 40 miles, but only after raising the antennas to a height of 200 feet. Based on this meager evidence that it could work, £60,000 was then appropriated for the project. Soon this first station was ready for witnessed trials.

And these trials would have to be classed as only limited in success, for the RDF set did, sometimes, detect formations of approaching aircraft; the range to the formation was readily determined, and it could occasionally identify the direction, roughly, a result of a last-minute upgrade in the antennas. Watson-Watt had ordered the receiving antennas to be set up in the traditional Watson-Watt direction-finder configuration: as Adcock pairs of stacked dipoles, and the members of the pairs were oriented East-West and North-South, respectively. The direction to an aircraft echo could be determined from the ratio of echo strength in the E-W lobe with respect to that in the N-S lobe. (The

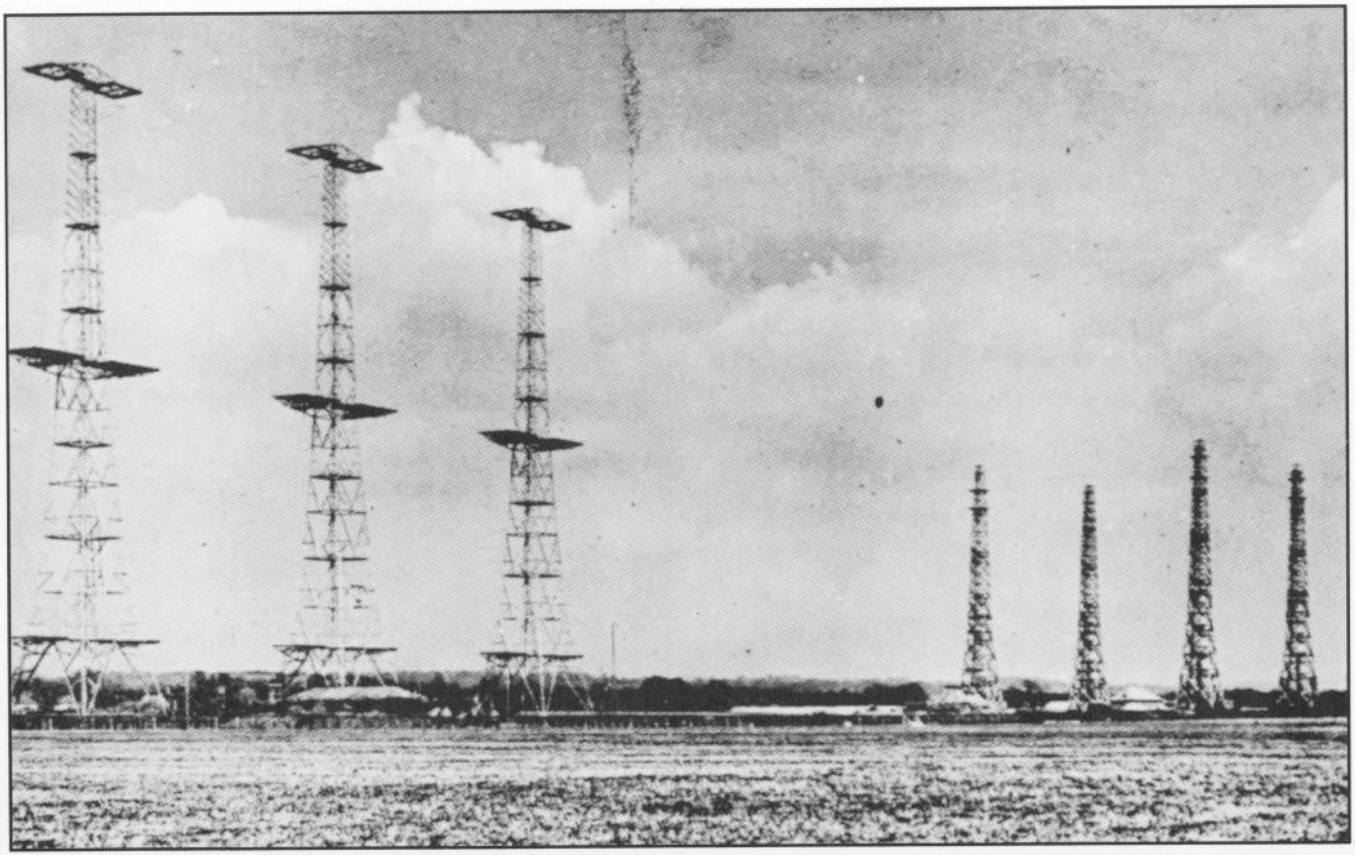

Figure 14. The complete Chain Home station at Dover. (Photo from Imperial War Museum.)

point that Watson-Watt had underestimated, with this method, was the crucial fact that it only works when the echo signals are very powerful, with respect to the radio noise, interference, and other echoes. For the pitifully weak echoes they were getting on this first radar, indicating the direction to the target was a matter of chance.) Nonetheless, echoes **had** been seen by the Air Ministry witnesses, and all were assured that in a short time these nagging problems would be fixed. And it was the only game in town.

Chain Home, Spits, and Hurris: Defense Against Bombers

The primary reason the Air Ministry continued to have faith in the RDF notion, after the mediocre trials of 1936, was that the newly appointed head of Fighter Command, Air Chief Marshal Sir Hugh "Stuffy" Dowding, had faith to spare. Dowding, who, while heading the Air Staff for R&D a year earlier, was the same official who had personally approved the original £12,000 for the project. Dowding knew that his small force of obsolete fighters had to be made to be as effective as a hundred times as many interceptors used conventionally, in the old "standing patrols" mode of the '30s. He believed, or rather, he hoped and prayed that RDF would make the difference. On a more personal level, he was also afraid that he might be going insane, and that the discovery of this fact might get him discharged, and then, where would that leave his precious tiny Fighter Command?

But another development was stirring, one which would also help immensely, in the battle against the bomber. In 1931, Reggie Mitchell, of the Supermarine Company, had won the Schneider Trophy for his entry in the international seaplane races. Dowding saw the sleek low-wing monoplane win the race, and asked Supermarine and Hawker, another favorite of Dowding's, to enter bids in the forthcoming Air Ministry requirement for new fighter planes. Both firms were awarded contracts for prototypes, and, by 1935, both the Supermarine Spitfire and the Hawker Hurricane were on the drawing boards. By 1936[33] both had flown successfully, and by mid-1938 both had entered RAF service. Here were fighters which could match speeds with anything Germany or France could put in the air.

For armament the thought was to use many fixed, small caliber, rapid-fire guns rather than the single or double cannons which were popular with the Germans, French, and Soviets. The theory was that many high-velocity, small-bore slugs hurled at an enemy plane would be very likely to inflict some damage, and any damage would have to be repaired, reducing the overall

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[33]The Hurricane, designed by Sidney Camm, first flew on 6 November, 1935. Mitchell's Spitfire had its maiden flight on 5 March 1936.

effectiveness of the enemy plane as a weapon. So both were equipped with eight fixed Browning .303 machine guns. Now, thought Dowding, with a handful of Spitfires and Hurricanes (fondly called "Spits" and Hurris"), and with a working RDF network, he could give Britain some measure of survival in the war he was certain would come, and soon.

The Spitfires were slightly faster than the Hurricanes, and so the strategy was to reserve the Spits for battle against the attacking bombers' escorting fighters, letting the Hurris go after the bombers, directly. Both Spits and Hurris would be vectored to the best interception points by the early warning afforded by RDF...it was hoped. Then, by rationing the interceptors such that only a few were committed at any single point, and at any one time, the total numbers of Spits and Hurris would be kept hidden from the Germans.

Chain Home Successes, and the Graf Zeppelin

The prototype Chain Home RDF station, at Orfordness, began to enjoy some successes, but locating the mock-attacking planes in azimuth was still a problem. Watson-Watt felt sure the problem would resolve itself as soon as the full network of stations was installed, as the various stations which detected a given incoming plane could triangulate on its position, eliminating the need for each station to locate the plane in all three dimensions. The third dimension, of course, was the height, or altitude of the enemy planes. Without knowledge of the incoming aircraft altitudes, the defending Spits and Hurris would have to resort to going to their intercept points at maximum altitude to avoid being jumped by the escorts. This would waste valuable time and fuel just getting there, which would permit a shorter time in battle before running out of fuel. Indeed, with even small errors in the altitude approximations one could bring a few Spitfires into a battle some 500 feet below the attacking escort fighters, rather than 700 feet above them, and the RAF could kiss a few Spits good-bye.

So, to get altitude discrimination the Chain Home RDF stations took on an aspect of tallness: with tall antennas, elevation angles of echoes (and derived altitudes of the planes making the echoes) were more accurately fixed. This meant **very** tall antenna towers, up to 350 feet in height, and a conversion to 23-26 MHz (in the 12-meter wavelength band) to provide range, coarse direction, and height information on incoming planes.

This frequency chosen for Chain Home had several good (and some bad) features. On the good side was the fact that ordinary transmitting vacuum tubes (valves) could be made to produce high power[34] in this part of the

[34]The CH transmitters routinely ran at 350 to 450 kW of power in each pulse.

spectrum. Also, receivers designed for shortwave communications were easy to design and construct, as were the antennas, themselves. Finally, and completely unappreciated by the system developers, at this frequency, the system just didn't look like a "radar," as everyone else came to perceive radars. With their tall transmitting towers and nest of slightly shorter receiving towers, these radars looked like pre-war shortwave radio stations. This same perception was held by the Germans. They were, at this time, developing radar, but with parabolic reflectors, or in "mattress" array configurations for antennas; these Chain Home systems looked like something else, and this would help keep them off the high-priority target lists of the *Luftwaffe*.

On the bad side, the frequency used sometimes allowed the radar transmission to be propagated by way of ionospheric refraction well beyond the horizon, to places deep within the continent. These radars operated in the shortwave band, and it is through ionospherically-refracted wave propagation[35] that shortwave signals travel over intercontinental distances. On occasion, echoes would be detected which were so far away that the time lapse between transmission and echo reception was greater than the time between successive transmission pulses. In other words, the echoing target was so far away that its echo was still enroute back to the radar receiver when the radar transmitter barked a second pulse. Thus, the echo was thought to come from the most recent transmitted pulse, whereas it came from a prior pulse. The range to the echoing object was therefore miscalculated, and in more than a few instances, fighter planes were scrambled to do combat with suspected bombers thought to be nearby, and over England, whereas they were deep in Europe. These false alarms didn't occur often, as most of the beyond-the-horizon echoes were from fixed things, like cities, mountain ranges, and other large artifacts. What the British had done, inadvertently, in Chain Home, was to create the first Over-the-Horizon (OTH) radar, about which more will be said, later.

Soon other Chain Home stations were being built, and a headquarters station[36] was created at a formerly sumptuous estate along the North Sea coast at Bawdsey Manor, just south of the prototype station at Orfordness. Here was the center of the RDF network, where all reports were filtered and sent onward to Bentley Priory, the air defense nerve center. At Bentley Priory WAAFs with

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[35]During the 1938-1944 period, the sunspot number was steadily declining, and it is this parameter which is best correlated with the highest frequencies which will propagate ionospherically. The British felt that the newer frequency of Chain Home, 23-26 MHz, was sufficiently high, based on the sunspot numbers, that the RDF signals would generally escape such long-range propagation during those lower-sunspot-activity years, and would continue through the ionosphere, rather than return to earth at great distances.

[36]The first CH production station.

croupier sticks pushed little flagged markers over a huge plastic map of Britain, marking the course of both enemy and RAF aircraft. Here, other inputs were added, as well, such as telephoned reports from coastwatchers. This is where interception decisions were made, and the signals to RAF Fighter Command units originated.

Soon Watson-Watt, Wilkins, Rowe, and their crews had installed 18 RDF stations in the Chain Home network. These stations had, by this time, grown towers fully 350 feet in height, and at least one of the stations (Dover) could be seen from the French coast, across the channel. Ever since the first RDF transmissions were emitted from Orfordness, the Germans had become curious about the strong buzzing signals they were intercepting all over Europe, traced, through direction-finding to be coming from the wooden shacks and their tall, spindly towers all along the coast of England. Some of these same RDF stations were regularly being photographed by crews of *Lufthansa* airliners.

Ironically, some of the German curiosity about the strange signals came from spy reports that, since 1935 or so, there had been a sudden English interest in "Death Rays." This interest, of course, is one and the same as the Wimperis order to Watson-Watt which led to the idea of using radar, in the first place. The more sober German scientists could not believe the Death Ray theory of the signals, but less rational minds prevailed at the top of the *Luftwaffe*, and investigations were ordered. In the spring of 1939 *Luftwaffe* General Wolfgang Martini[37] was directed to look into the English towers and their signals. From the pulsed nature of the signals he suspected these things were some kind of radar, since his own country had built, by this time, the *Seetakt*[38] anti-shipping radar, and the *Freya*[39] aircraft-detecting radar. This latter radar had fallen out of favor with Goering and Hitler, as being decidedly defensive in nature. But despite the radar-like signals being intercepted the physical appearance of the lacework towers didn't look right at all.

Martini considered flying aircraft with receivers along the English coast in order to collect clean examples of the strange signals, but realized that if these were radars, the aircraft would be detected, and their mission would be revealed

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[37] *Luftwaffe* Director-General of Air Signals.

[38] *Seetakt*, or Coastwatcher, is described in US War Dept TM E-11-219 as a 350-390 MHz early-warning set designed to watch waterways for shipping. It used push-pull doorknob tubes in its transmitter, and acorn tubes in the receiver.

[39] *Freya* was built by Gema in two models. The "Limber" model was mounted on an 88mm flak gun base, operated on 125 MHz, using push-pull triodes in its power oscillator (transmitter), and used a receiver much like that of Seetakt. The "Pole" model was taller, using three rows of dipoles in its antenna, vice the Limber model's two rows.

by the circuitous flying routes. He needed a more stealthy receiving platform, one which could hover for hours, outwaiting any sneaky English tricks, like shutting down station after station as the ferreting aircraft came near. At Frankfurt, Martini ordered the old *Graf Zeppelin* out of mothballs, where it had been ever since the loss of the *Hindenburg* at Lakehurst.[40] The *Graf Zeppelin* was hurriedly outfitted with receiving gear and external antenna wires, to enable the pickup of the strange signals. The enormous airship was readied, and set sail for the English coast on 7 May, 1939, just two years and a day after the *Hindenburg* disaster. The airship proceeded across the North Sea and then turned to approach Bawdsey Manor, directly. This RDF station was selected for examination simply because it was close to the Dutch coast, and it was obviously one of the radio noisemakers. At this stately manor, the 350-foot towers stood out, compared with the other installations, which were generally in barren, remote locations. Spectacular telephoto pictures were taken of the manor, its towers, and everything thought to be important. As luck would have it though, the airship's receiving equipment failed, and no useful recordings of the RDF signals were collected. The approach of the airship was clearly seen by the RDF operators, who were perplexed by the echo which moved at but 75 miles per hour, and at only 2000 feet altitude. Since it made no threatening moves toward any militarily useful target, the British let it alone. More importantly, the British did not alter the RDF signals transmitting characteristics, just in case the Germans were listening. By not reacting at all, the Brits hoped that the Germans would assume the airship had not been detected.

Upon the airship's return to Germany, the on-board receiving equipment was tested quickly by a large group of technicians, and many simultaneous repairs and modifications were made, such that the technicians could not be certain whether the equipment ever worked properly the first time. Here was a rare case where the stereotypically German methodical approach was not followed, and too many hands went into the equipment at once. Analysis of the photographs taken on the trip revealed that the taller towers were for transmitting at relatively high power, based on the sizes of porcelain insulators used. The antenna wires' lengths indicated that if the towers were used for transmitting, as was suspected, the frequency transmitted would correlate well with the frequency of the buzzing signals that the Germans had been receiving for months; these were the noise-like signals which prompted the interest in the towers in the first place.

A second flight was called for, and proceeded in August, 1939, this time with well-designed equipment aboard, including calibrating signal generators

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[40]The *Hindenburg* burned while being moored at Lakehurst, on 6 May 1937, leading to the grounding of all large hydrogen-filled passenger dirigibles.

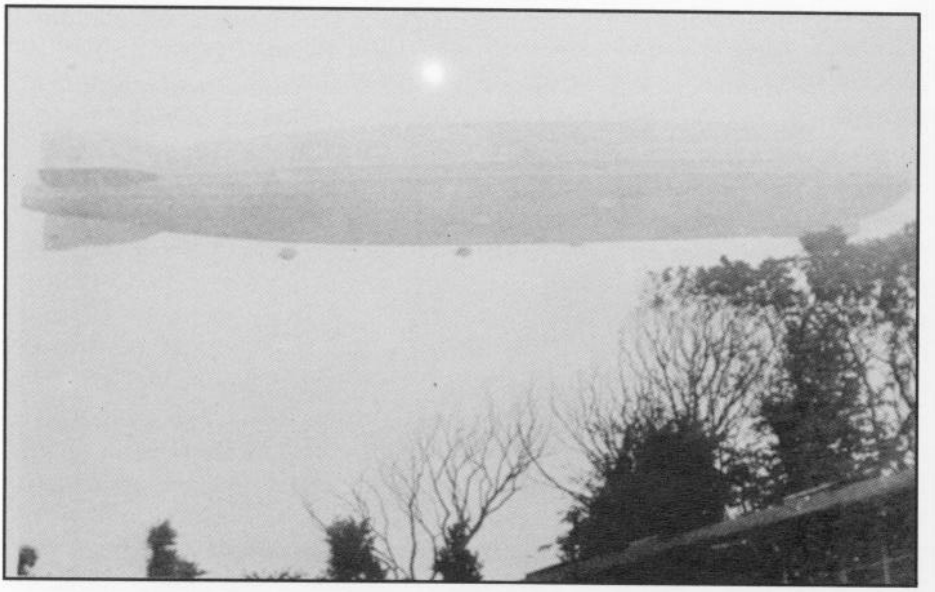

Figure 15. Photo of *Graf Zeppelin*, seen in the morning fog just offshore from Aldeburgh, north of Orfordness, on her second ferret mission against Chain Home signals. On this flight, *Graf Zeppelin* could detect radio signals from 6 MHz through 160 MHz, using four receivers, plus spares, and a pair of calibrating signal generators.

(Photo courtesy P. Abercrombie, AWRE, Swansea.)

so that the receivers could be checked in flight. This flight sailed back and forth only a few miles offshore, in front of two of the RDF stations, in hazy weather. The airship lingered so long that several pictures were taken of the goliath by anxious citizens while it carried out its ferreting duty. By a fantastic coincidence, a segment of the growing intercommunications network linking the Chain Home stations in that area was undergoing acceptance tests that day, and so the RDF transmitters were shut down to avoid interference with the tests. The *Graf Zeppelin* again returned to Germany without evidence that the strange spindly towers and their shacks produced transmissions.

Martini was satisfied, finally, that the British did not have an effective radar system, but he allowed that the towers might be **receiving** systems (which wouldn't have emitted any signals for the *Graf Zeppelin* to intercept) which cooperated with some sort of beam to guide future British bombers. He was easily persuaded of this theory, because his own forces had been installing an elaborate beam-generating system of their own, called *Knickebein*. This system placed narrow radio beams across the channel, and across England. The beams could be swung to cross over desired targets to be bombed. Then a second beam originating in northern Germany or Holland was laid across the first, marking

the bomb-drop point. All German bombers had to do was fly the first beam, and drop their load of bombs when they crossed the second beam. (The system worked quite well, until the Brits got wise to it and set up their own beams, designed to confuse the German pilots, and causing them to unload over open fields. The story of the discovery of the *Knickebein* beams is a classic in countermeasures study, one which will be described later in this series.) Besides, thought Martini, if those ramshackle huts and towers proved to be troublesome, they could always be wiped out in a jiffy.

The Death Ray, Again, and Chain Home Low

In September, 1939, Hitler invaded Poland, and with Danzig already in hand and Czechoslovakia dismembered and in his camp, his plan was to control most of continental Europe, toppling each country in turn, either by military action, internal foment and disintegration, or outright intimidation. Through poorly strategized alliances, some of these likely sovereign collapses would impact Britain, and the British knew, as a metaphysical certainty, that they were "on Hitler's list." One of these alliances threw Britain into a state of war with Germany as soon as the invasion of Poland began on the first of September. Still, a real war did not come to Britain immediately, except in the Channel and on the high seas.

It was at this time that the British got a dose of the same Death-Ray scare which they had inadvertently bestowed upon the Germans, and which caused the Germans to bore into the buzzing signals coming from the English coastline. *Reichskanzler* Hitler was broadcasting, on *Deutsche Welle*, one of his ranting speeches from a just "liberated" Danzig, in September, 1939, in which he denounced any army which was reckless enough to stand up to the *Wehrmacht*. His use of the German language was, as usual, crude, and idiomatic. He screamed something about his forces possessing weapons the enemy couldn't even comprehend, weapons which would destroy their minds! Or, at least, that is what the English translators came up with. The panic which ensued, in England, was spectacular. Many scientists felt he had been referring to atomic energy; some thought it was a nuclear-powered electromagnetic ray which would incapacitate people instantly. The theories were flying hot and heavy, each scientist convincing himself that the Germans were years ahead of the West, and had actually perfected some sort of "Buck Rogers" mind-warping ray-gun. Then someone, probably R. V. Jones, who worked for the PM's pet scientist, Lindemann, decided to get the speech translated from the beginning. This time, the phrase "...which would destroy their minds..." came out, "...which would boggle the imagination...." In this interpretation, it was just standard Hitler rhetoric. So Herr Hitler was just bragging, probably about his *Luftwaffe*, which was, admittedly, quite good.

By late 1939 Dowding had become disenchanted with the performance of the Chain Home (CH) system against **low-flying** mock attack exercises. Any time the RDF antennas were phased to lower their beams, the reflections from the ground and sea were overwhelming. This "backscatter," or clutter, was similar to the blinding glare from the sea surface one gets when one looks into eastern seas in midmorning. In August, 1939, the problem was attacked by the construction of the first of the Chain Home Low (CHL) stations, again first tried at Orfordness. In Chain Home Low, the wavelength was reduced from 12 meters to less than 2 meters, narrowing the beam in elevation, so that it could be aimed low but still not skim the sea surface, which is what brought up the nasty clutter. At this higher frequency, though, the available transmitting power[41] was significantly lower than with the CH RDF station, and it was not possible to further dilute the transmitted energy by scanning the beam up and down. This meant that the altitude of any plane detected could not be determined. But by pairing the CHL station with a companion CH station, any aircraft "seen" at all on CHL, but not on CH, was presumed to be at low altitude, and could be jumped by a fighter at a moderate altitude. By November, the first operational CHL station was in place. The others followed quickly. Soon all these stations would have to be pressed into operational service, against an enemy whose nationality had become clear.

This was a very somber time for Britain, France, and the low countries. Each knew that Hitler was capable of moving in any direction, and each knew that there could be no dependence of one country upon another, owing to the lightning speed of German attacks so well displayed in Poland, and the political anxiety over committing servicemen to die for another country, an anxiety which made procrastination into an art form. The *Blitzkriegs* against Czechoslovakia and Poland left the west wide-eyed and slack-jawed. At this point Hitler wasn't sure he had to attack anyone; he thought they might all collapse, one by one, just out of fear. He was nearly right.

On the 4th of April, 1940, the PM, Chamberlain, trying to show that he was not intimidated, spoke before Parliament, remarking how stupid Hitler had been for not having moved immediately through the Low Countries, France, and England, upon taking Poland. He said Hitler had "missed the train," and now it was too late, for the unconquered rest of Europe was now a single pillar of solidarity. Five days later Hitler responded by sweeping through the low countries, and by sending infiltrators into Norway. A total of six Norwegian

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[41]The 2-meter CHL transmitter used the usual pair of triode tubes, in push-pull arrangement. At this time, only the Americans (NRL and the Signal Corps) had the ring oscillator, which would have significantly improved the CHL power output.

ports were invaded simultaneously on the 9th of April, including Narvik, in the far north, this last-mentioned fact unknown to the British.

It was now time to "fish or cut bait" for Britain, as the invasion of Poland automatically meant they had been at war with Germany for six months already. True, Britain had been sending troops into the continent to bolster France and the Low Countries, but, so far, the war seemed remote and disconnected from Britain. But Hitler's takeover of Denmark, and simultaneous infiltration of Oslo, was the last straw, forcing Britain's hand. The time for effective action was at hand because Britain's precious Scapa Flow naval base was being threatened.[42] In Norway, then, was a place for Britain to express herself, with Churchill's Royal Navy leading the way. So Churchill had a plan. The Brits could slip over to far northern Norway, land a handful of commandos to prevent a German landing, and drive any Germans they found back south, perhaps to Germany. Better yet, land some commandos, take over an airfield or two, and let the RAF, based at these airfields, drive the Germans out. That was Churchill's plan.

On the 10th of April,[43] the Royal Navy sent five modern destroyers into the harbor at Narvik, where, to the surprise of all, they discovered a small force of *Kriegsmarine* destroyers which they scattered, sinking two and running one aground. But then, five more German warships emerged from the foggy fjords, and cut the British force to pieces. Only two of the Royal Navy destroyers escaped undamaged back to England. The commandos had been landed, but their winter gear was aboard a different ship, which did not offload, so they became trapped. On the 14th fresh commandos were landed, but not supported until the 24th, when the battleship *HMS Warspite* and three cruisers bombarded the port.[44] Meanwhile, the RAF fighter-bombers (Fairey Battles and Gloster Gladiators, not Spits or Hurris) which had slipped into Narvik's airfield in the synchronized raid on the 10th were found by the *Luftwaffe*, and were destroyed. On the brighter side, the Royal Navy submarine service performed well, sinking a U-Boat and damaging the pocket battleship *Lutzow*. And, with the added firepower of *HMS Warspite*, the return to Narvik harbor by nine Royal Navy destroyers did succeed in sinking or grounding all of the German destroyers there on the 13th of April. But the commandos and RAF planes were lost. What an ignominious start for a war. Chamberlain took the blame, and was sacked on the 10th of May, while the architect of the Narvik debacle, Winston Churchill, replaced him as PM.

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[42]And, on both the 2nd and 23rd of April, the *Luftwaffe* bombed the naval base.

[43]The Narvik battles of April 1940 are summarized in the 1979 book, *Nazi Europe*, pp214-224, by Marshall Cavendish Books, Ltd., a compilation of global radio and newspaper accounts of the time.

[44]Böttger, Gerd, *Narvik im Bild*, pp18ff, Gerhard Stalling Verlag, Berlin, 1941.

In France and the low countries, things went even worse. Here, in May and June, disaster followed disaster, with the largest British blunder being the shipping of many of her Hawker Hurricanes and Supermarine Spitfires over to France for ground support of their expeditionary forces, to be chewed up by a vastly larger fleet of Messerschmitt Bf109s and Me 110s. Having no exact match for the German Junkers 87 *Stuka* dive bomber, the RAF felt obliged to send in something with which to dive-bomb, so they shipped over Fairey Battles, delicate single-engine bombers. They were all lost to accurate fire from 88-mm flak guns. Dowding fought bitterly against sending more planes over to France, arguing that without Watson-Watt's RDF they couldn't compete against the superior numbers of similarly-performing Messerschmitts. He claimed they should dig in back in England, use the Chain Home system in tight cooperation with the Spits and Hurris they had left, and make Goering come to them.

What Dowding did not know was that the Germans were operating a very good aircraft-tracking radar at the time, the *Freya*. **Any** knowledge of the *Freya* deployment would have made it far easier for him to convince Air Command to abandon the continent much earlier. For those few Air Ministry officials who were "in the know" about the Chain Home radar network, and how it was planned to augment the effectiveness of the RAF Fighter Command interceptors, such knowledge might have prompted them never to have sent RAF planes to the continent in the first place. On the other hand, **full** knowledge of the German radar system would have revealed that those radars were poorly tied to each other, and to the interception fighter planes, very much **unlike** the situation in Britain, and might have convinced the RAF to send over more Spits.

The Air Ministry finally listened to Dowding, after they had wasted almost half of the inventory of Spitfires and Hurricanes, and nearly all the Fairey Battles available. By the last week of May the British Expeditionary Force had been squeezed to Dunkirk, and had to be evacuated by a fleet of yachts, fishing schooners, whaleboats, dories, and Royal Navy ships, and during which evacuation the balance of the RAF fought off the *Luftwaffe*, which was out to destroy the rest of the British force.

The Battle of Britain

So much for the "phony war." It was July 1940, and the real Battle of Britain now began. The German plan was to carry out an invasion of the British Isles, but that would necessitate first removing the threat to the invasion force posed by the RAF. Therefore, the Battle began with the German effort to destroy the RAF. Hermann Goering had bragged to Hitler that in a week his *Luftwaffe* would destroy every aircraft in Britain. Ten days, at the absolute most. With

some luck, seeing their RAF disappear before their eyes could prompt the English to sue for peace, making an actual fighting invasion unnecessary. The overall plan was called *Seelöwe*, or Sea lion, and was to begin with Goering's lightning attacks on all RAF bases. The invasion plans began to churn. The British became paranoid over any congregation of barges or boats in the Channel, and RAF raids on them became commonplace. Goering felt he might be able to draw the RAF into the Channel in force, where he could let attrition take its toll. But, destroying the RAF would not be as simple as that.

For one thing, the Germans had inadequate intelligence about which little fields were actual RAF bases, and which were private fields and simple storage warehouses. So they wasted many flights trying to destroy empty fields, old airfields having a few ancient planes parked, and the like. Also, even when the real bases were found, the *Luftwaffe* bombers scattered their bombs all over the English countryside, instead of hitting the airfields, directly. The big difference in bombing in England, compared with the surgical bombing of Poland, France, the low countries, and Channel shipping was that England had to be reached with large, swift, level-bombers, and not with the famed Junkers 87 *Stuka* dive-bomber. The *Stuka* was superbly accurate, but so slow that it could not be defended against an aggressive interceptor-fighter force. The Heinkel 111 twin-engine bomber, on the other hand, like the Messerschmitt 110, was fast and hard to shoot down, but dropped its bombs while in level flight. Without a very good bomb-aiming mechanism, many of the bombs went wide of the mark. In time, though, bombing accuracy improved, but not through the use of a better bombsight. The German pilots were slowly getting the hang of the *Knickebein* beam-follower system, and they were being introduced to a new system, called *X-Gerät*.

Special British Lancaster and Liberator aircraft, dubbed "Ferrets," carried skilled radio-operator crewmen and special (sometimes unofficial) intercept radio receivers. Many Lancaster ferrets were outfitted with Hallicrafters S-27 receivers, swept up from all the amateur radio suppliers in New York, by an alert Royal Signals Establishment clerk during an official visit to the 'states and Canada a few months earlier. In flights over England, where R. V. Jones[45] suspected that the Germans had aimed navigation signals from the continent, the ferrets had noticed "hot spots" of 30 MHz signals, and these hot spots would move about, first here, then there. The hot spots had dots on one side and dashes on the other. In the middle, the dots and dashes intermingled, forming a continuous signal. Then, it was found that the hot spots were elongated, often being continuous, in one direction, for hundreds of miles, but only 500 to 1000 yards wide.

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[45]Jones, R.V., *The Wizard War*, pp92ff, Coward, McCann, and Geoghegan, New York, 1978.

These were beams, not spots, and they all pointed away from apparent sources in Germany and Holland. R. V. Jones immediately reasoned that the beams were to guide German bombers to target, and he guessed that there would be some sort of crossing beam along the main beam, indicating where the target to be bombed was located. Jones also noted that the frequency chosen for this beam system was just outside the usual coverage of standard shortwave receivers, and, hence, would be very unlikely to be discovered by casual listening. The Germans probably did not anticipate the British use of the Hallicrafters set. Repeatedly, test pilot Blucke (the same pilot who first flew against Watson-Watt's Daventry "radar") tried to find the second (crossing) beam, and finally, he found one, just a hour before a German raid on the Rolls-Royce Merlin engine plants at Derby, over which he found the beam.

A second effort got underway, immediately. All shot-down Heinkels were examined for mysterious receivers, and in several, they found Lorenz radios, preset to specific spot-frequencies, 31.5 or 33.5 MHz. Furthermore, two Heinkels yielded paper notes which referred to the spot frequencies, to the word *Knickebein*, and to two cities in Germany, Husum and Kleve. These were already suspected as being the *Knickebein* beam transmitting stations, based on simply extending the discovered portions of the beams. Jones, who had pieced this picture together, was called before Churchill, now Prime Minister, and his war staff. Jones explained his hypothesis, his pilot's findings, and the evidence in the Heinkels. He suggested that they immediately jam the beams, produce false cross beams, or produce false longitudinal beams. Churchill's scientist, Lindemann, sitting at Winston's elbow, insisted on an elaborate scheme, sowing the beams with aerial mines, held aloft by parachutes or balloons, for the bombers to fly into. What was finally done, and quite effectively, too, was a combination of jamming of the beam frequencies and the erection of false beams, the result being a marked decrease in *Luftwaffe* bombing accuracy.

To combat the false beams and jamming, the *Luftwaffe* then began using standard *Deutsche Welle* broadcasting transmitters to produce the beams, transmitting propaganda program material. The signals, usually flooding all of England, would be squeezed into a very narrow *Knickebein*-like beam just before a raid was scheduled, the beam falling directly over the target of the day. This beam was followed by the bombers, day or night. British listeners in London noticed the propaganda broadcasts getting markedly louder in some places, markedly dimmer in others, just before each air raid, and they noted that the bombs always fell on the places where the broadcasts had become loud. After some 20 or more of these alert listeners had related their experiences with the propaganda to Ministry of Defence officials, the MoD told Lindemann about it. He alerted R. V. Jones to take action against these broadcasts, as they had against *Knickebein*. The resultant

British fake broadcasts reduced the effectiveness of the *Luftwaffe* attacks after that.

The German losses in aircraft, and, more telling, in air crews, began to mount, and, at times, for strange reasons. Owing to a shortage of Spitfires, Fighter Command sent a squadron of Boulton-Paul Defiants to deal with a flight of Messerschmitt 110s and a few Bf109s, which were harassing RAF bombers headed for the Channel. Mistaking the Defiants for Hurricanes, the German pilots maneuvered skillfully to avoid getting in front of the Defiants, where a Hurricane would lay down deadly fire. The Defiant, though, had only a rear dorsal gun turret, and so the RAF squadron was able to surprise and down some 17 or 18 *Luftwaffe* planes in a few minutes. A "trick" like this could only happen once, however. Repeating the event later, on the 19th of July, nine Defiants attacked 15 Bf109s. Not fooled, the Messerschmitts knocked down six of the RAF planes in less than a minute. Two more, damaged in the fight, crashed on landing.

Each German raid left a few craters in some RAF airfields, made many craters in open areas, and returned with some Heinkels and Messerschmitt escorts missing. The British were beginning to learn how to coordinate the radar detections with the optimum fighter deployment. Everywhere the Germans attacked, there were a few Hurricanes there to meet the bombers, and Spits ready for the escorts. What Goering wanted was to sucker the whole RAF fighter command into the air at once, so he could destroy many more per raid, but Dowding knew better. He rationed the fighters into battle, never putting all his eggs into one basket.

There were losses in the RAF fighter squadrons, too. But the German losses were more costly, as any damaged plane was likely to be lost before getting home, and any crewmen shot down over Britain were lost to the *Luftwaffe*, forever. The July score had it: RAF: 77 losses; *Luftwaffe*: 216 losses.[46] Goering began to get some heat from *der Führer*. Just when was this crippled RAF going to be completely destroyed? *Der Dicke* ("the fat one," as Hitler[47] called him) had promised, first, a week, then a few weeks, then a few more weeks, and on and on. By this time, Martini, chief air signals officer, became convinced that the British were, in fact, employing long-range radar to know where to position their interceptors. Heretofore, the general impression was that the Brits were employing standing patrols[48] of interceptors, a very costly technique. He kept bringing it up to Goering, suggesting, with remarkable accuracy, that those skinny towers all over the English coast were, in fact, radars, and these radars were the key to the success

[46]Cavendish Books, Ltd., *Nazi Europe*, p337.

[47]Hitler also referred to Goering as *die dicke Sau* (the fat sow).

[48]Cavendish Books, Ltd., *op cit*, p351.

of the RAF in dealing with *Luftwaffe* planes. Goering had had enough. "All right, **all right**, we'll **destroy** the damn towers!" he finally shouted, and he turned his bomber fleet loose on seven of the Chain Home stations.[49]

The Futile Attack on Chain Home

The British had been curious why the Germans had never attacked the RDF sites before. In preparation for such an attack, they had hidden duplicate equipment near each RDF site, ready for instant replacement. The attack came, but the towers were extremely hard to get with a direct hit.[50] And, being of open framework, they let most of the bomb blast fragments go on through, causing little damage. The shacks were something else; they were blasted down, usually wounding or killing the operators, but fresh huts, equipment, and operators were standing by, and were rushed into the site, just as soon as the *Luftwaffe* turned their backs to return. And the RAF had their usual score, three or four German planes mortally crippled or shot down for each RAF fighter downed. By the time the *Luftwaffe* had returned to base, the RDFs were back at full power, so that the very next German raids were met, as usual, by Spits and Hurris, no matter where the next English target happened to be located. Goering sought out Martini, and said his "I **told** you so!" Quite obviously, the British were using something else to guide their interceptors, or else they were just plain lucky. Goering's official excuse for not pursuing the attacks on the radar stations was that he doubted that the Luftwaffe could damage them seriously,[51] indicating, surely, that he did not appreciate the critical connection between the radars and Fighter Command.

The deadline for the *Seelöwe* invasion came and went, and again and again Hitler asked *der Dicke* just exactly when.....

But, back in Britain's RAF brain trust, all was not going so well. Dowding was fighting a battle for time, and during this battle, the RAF fighter numbers continued to shrink. He realized that it would be foolish to send big forces of interceptors out to meet the German aircraft, because more would be shot down on both sides, and the RAF couldn't afford any more losses. Yet higher powers in the Air Ministry seemed to ignore this little fact, and sent overenthusiastic commanders like Douglas Bader to head up wings of Spits, based around London. Bader was sort of a hero, having made his reputation by stunt-flying any plane he jumped into. In inverted flight at essentially zero altitude, one day many years earlier, he

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[49]Fisher, D.E., *A Race on the Edge of Time*, pp200ff, McGraw-Hill, 1988.
[50]Fleming, Peter, *Operation Sea Lion*, Chapter 15, Simon & Schuster, 1957.
[51]*ibid.*

didn't quite keep enough forward pressure on the joystick, and pranged his craft all over a brush-covered field, losing both legs as a result. He pressured his superiors to let him continue to fly, even with artificial legs. (Much later in the war, Bader would finally get shot down over Germany. On pulling him out of his burning plane, German soldiers accidentally separated him from his entrapped artificial legs. They were amazed, and treated him as a hero, even going to the trouble of recovering his somewhat charred legs from the plane wreckage.)

Bader was anxious to get into the fight, and was constantly disappointed in not hearing his squadrons' numbers being called for intercept duty. Finally, the Chain Home RDF network indicated a raid headed for London, so his number was called, and he sent up his entire wing, rather than the standard two-flights-of-three-each. By God, he'd show them. He'd knock down a hundred jerries, and then they'd take notice. It took him over 40 minutes to get his whole force off the ground and formed-up, and by that time the race to the intercept point was won by the Germans. So it was the jerries who jumped the RAF, not the other way around, like it was supposed to be. Bader came limping home, minus two dozen planes, while several RAF airfields and factories were destroyed, and Dowding was furious. To make matters worse, Dowding's problem with his mind, one which kept him awake deep into the night, was getting worse.[52] All night he would be visited by his long-dead wife and all of his many RAF fighter pilots who had been killed in action. They came in crowds, now, and talked to him for hours every night. He was afraid he was running out of time, before he cracked, completely. Bader's recklessness didn't help one bit. Twice more Bader tried this stunt, and each time he failed to carry out the intercept on time. Bader argued for more warning time, but the Chain Home system just couldn't give any more.

After months of indecisive attacks on RAF bases, factories, and supporting sites, like the radars, themselves, it was the *Luftwaffe* that was running out of time. *Seelöwe* had a definite timetable, even if it seemed to be constantly pushed off into the future. The date for the invasion had to be before the rainy winter season of southern Britain. The rest of the *Wehrmacht*[53] was ready; but the RAF was still a threat to any invasion force, and the *Kriegsmarine* refused to consider providing the transportation for the invasion until they heard a convincing statement that the RAF ceased to exist.

Then, on the 25th of August, 1940, RAF Bomber Command made a tactical mistake; they bombed a German city. Not the factories, which were

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[52]Fisher, D.E., *op cit.*, pp162ff.

[53]Rotterdam, especially, was the scene of extensive invasion build-up, including the assembly of hundreds of invasion barges.

considered fair game, but the business and residential parts of a city. And not any city, but Berlin. Goering had boasted that if even a single English bomb ever fell on Berlin, they could all call him *herr Meyer*, considered by the Nazis to be a Jewish name.

Hitler went into a rage. He summoned *herr Meyer*, and demanded that the RAF be eliminated, and furthermore, by the 11th of September, the final date for *Seelöwe*. Goering went berserk, thinking only about the humiliation he had to suffer at the hands of RAF Bomber Command, and so he immediately ordered the retaliatory bombing of London, by enormous bomber forces. He reasoned that if the Germans finally bombed the non-industrial heart of London, it might bait the RAF into a reckless all-out showing, which his Messerschmitt Bf109 escorts could take care of.

Another Allied development, however, interfered with the carrying out of this latest Goering order. One of the last things smuggled out of a defeated Poland, and into England, by Polish intelligence officers, was a set of hand-made *Enigma*[54] cipher machines, plus the *Bombas*[55] used to break the *Enigma* ciphers. British signals intelligence, based at Bletchley Park, had, by mid-1940, mastered these machines, and was able to read intercepted German military messages as quickly as could the intended recipients. The *Luftwaffe* orders were, therefore, being read by the British in real-time.

In the first attack the Chain Home system worked quite well, and the bomber formations were anticipated and intercepted, but considerable damage was done to London. *Luftwaffe* bombers that failed to return inflamed Goering even more. How could the British keep coming up with more Spitfires and Hurricanes, and always at exactly the right time and place? Martini insisted that the coastal RDF stations were cooperating with RAF Fighter Command to position the interceptors optimally for the German attacks. Goering shot back the question, "...hadn't he diverted at least three raids on those so-called radar stations on the English coast? And with what result?" Larger raids were ordered, again for London. These raids were detected with plenty of lead time, thanks in large part to the deciphering of intercepted German orders by Bletchley Park, and this time Bader's all-out tactics worked quite well. The German losses in both bombers and escorting Bf109s were much larger, but

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[54]Highly automated German multi-rotor cipher machine. The operator set the rotors to the key positions for the day (and sometimes, for the hour), and typed in the message to be enciphered. A similar machine deciphered the message once its rotors were set to the same key as the enciphering machine.

[55]Polish cipher experts had developed huge machines which quickly tested each key-stream possibility against the cipher text of a message. The machines, called *Bombas* (English copies were *Bombes*), were, in effect, super-speed *Enigma* machines, themselves, and they looked for a short spurt of intelligible text upon cycling candidate rotor positions through the machine.

about 40 of Bader's planes were also lost or seriously damaged. Then, as was commonplace on both sides in the air war, to the surviving German escort pilots it seemed that they had shot down over 200 English fighter planes, and this was a number Goering had been dying to hear.[56] Now, finally, thought *der Dicke*, the RAF fighters had taken the bait, had been drawn into the battle in full force, and were now practically all gone. The 11th of September passed. The final, final, date for *Seelöwe* was now 17 September.

On the 15th, Goering sent his maximum force to London, expecting reduced opposition.[57] His orders had been intercepted by the British signals intelligence unit at Bletchley Park, were quickly decoded, and were being read by the Bawdsey Manor CH Central and Bentley Priory air battle coordinators even before the Messerschmitt pilots could read them. RAF Fighter Command was ready, including Bader's huge Sector Station wing. The Spitfires were moved to ideal fields from which to attack the escorts from out of the sun, and they bored directly into the formations of Bf109s, scattering them, still over a hundred miles from London. Two thousand feet below the first waves of Hurricanes attacked the bombers head-on, breaking up their formations. With the formations widened into huge loose strings, the Messerschmitts lost control, as they couldn't shepherd them all, and the outer bombers were systematically shot down. The Bf109 escorts, forced into dogfights still 60 and 70 miles from London, couldn't hold on, and began returning home, their "low fuel" lights winking at the pilots. Then the bomber force was decimated.[58]

When the crippled remnants got back to Germany, Goering went into a rage. The bomber pilots, angered at having insufficient escort power in the face of what seemed to be a spectacularly powerful RAF fighter force, returned to their bases in Germany in the same formations as when they had left, hours before, with all the missing-plane gaps brazenly displayed. Formerly, any bomber losses had been more or less hidden from the citizenry by the re-formation of surviving planes into new, tight returning formations. This time the pilots showed off their missing mates' airspaces. Goering was unsympathetic and unimpressed. He astonished the crews by ordering all the planes refueled, rearmed, and returned to London, the same day. Again Bletchley Park deciphered the order, and had it in the hands of an equally

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[56]Fleming, Peter, *loc cit.*

[57]Not every Goering order was so impetuous. He had correctly aimed several raids on the inner Fighter Command bases, the Sector Stations, which were key to the coordination of Fighter Command's tiers of interception strength against German Bombers. During these raids, the RAF was noticeably less effective, and it is a complete mystery why he didn't follow them up with a few more such raids.

[58]Fleming, Peter, *loc cit.*

astonished Fighter Command and Dowding before the German crews were informed of their preemptory new mission. Bader and the other fighter wing commanders went all out, knowing that these German crews would be exhausted and in a hurry.

Without sufficient time to send the Bf109 escorts ahead to forward bases for coordinated refueling before the raid, everything was launched toward London. The escorts, flying faster than the bombers, did get to some French fields for refueling, but then lost the main formation. In chaos, the bombers, and some of the (un)lucky Messerschmitts approached London, and ran smack into wave after wave of fresh Spits and Hurris. The bomber force was reduced to stragglers, and the bombs fell all over the suburbs, along with burning aircraft. On that day the *Luftwaffe* had lost 185 aircraft in the two raids.[59] The Battle of Britain was essentially over. On the 17th of September Bletchley Park intercepted a message from Hitler's General Staff to the invasion engineer battalions, who had been waiting in Rotterdam for six months for their work to begin, telling them to return for reassignment to the East. Hitler was through with *der Dicke's* promises and with *Seelöwe*. He had been developing a growing dislike for *blitzkrieg* methods, especially when they didn't work, so now he would turn his attention to Russia, where his favorite strategy, the siege, could be exercised.

For a week or so, the skies over England were very quiet. Their "finest hour" was over. Goering, however, would continue the attacks on England's cities, vowing to destroy England from the air, but at night.

The Blitz

That first RAF attack on Berlin, which may have seemed so foolhardy, set into motion retaliation by the Nazis, not in kind, but multiplied a hundredfold. In retrospect, even though it caused the destruction of great parts of Britain's finest old cities, it probably saved the RAF, and saved civilization from the almost certain invasion and takeover of Britain. Without the recklessness of Goering's all-out destruction orders, the *Luftwaffe* would not have suffered nearly so many losses in August and September, 1940, and, with cooler heads, the Germans might have succeeded in eroding RAF Fighter Command forces down to zero. Now the die was cast, and both sides continued the mutual destruction efforts against each other's civil structures. With radar, though, the bomber was not always going to get through, since bomber raids could be intercepted by radar-directed fighter planes, manned by skilled pilots/gunners, so long as these crewmen could ultimately see to shoot at the bombers.

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[59]Miller, John A., *Men and Volts at War*, pp133-134, McGraw-Hill, 1947.

Both sides resorted to night bombing raids, the rationale being that the bombers wouldn't be so vulnerable to interceptors if they couldn't be seen, and the cities, once afire, could be found rather easily. The plan, on both sides, was to use a few "pathfinder" planes to drop flares or incendiary bombs to mark the target city; then the main force would unload on the marks. Just how the pathfinders were to find the target city was never completely resolved, but the *Knickebein* and *X-Gerät* beams were supposed to help, for the *Luftwaffe*. For the British, a precision navigation system called GEE was placed in operation. It put a navigation gridwork over Europe, similar to the that of the later LORAN system. Here, pulsed radio signals, from two or more stations, are received in the bomber, who determines his own position by calculations based on the timing of the pulses received, with respect to each other. In the event GEE became jammed, as the Brits were doing to *Knickebein*, a second system, used in the pathfinder aircraft only, called Oboe, was developed. It used pulse signals, also, but the calculations were made on the ground, back in Britain, and were radioed to the bomber. The trick was for the bomber to fly a perfectly circular course, centered on the Oboe transmitter in England. The diameter of the circle was set by computation to lead the pathfinder directly over the target. Oboe produced no beams over Germany, and so was never recognized by the Germans. Furthermore, the pathfinder bombers were now nearly always deHavilland Mosquitoes, which were so fast and could fly so high that they were rarely shot down.

The uselessness of the *Knickebein* beams, once Jones figured them out and jammed them,[60] forced the Germans to use a new system, *X-Gerät.* This 70-MHz system placed beams over Britain, as did the *Knickebein* method, but the beams were very narrow and so accurate in position that the existing maps of England were found to be in error, with respect to the beams. After map correction, the *X-Gerät* transmitter antenna was carefully rotated to aim the beam, checked by a truck-mounted calibration receiver. The truck was carefully hand-positioned to within 5 millimeters of its calculated position. In an actual German bomber attack on Birmingham, for example, the mean bomb cluster line fell within 100 yards of the calculated *X-Gerät* line. The system's weakness was the same as Knickebein's: the beams could be found, not necessarily without difficulty, and then jammed. Much of the blind searching for these new beams was eliminated by the improvements in German message intercept and deciphering at Bletchley Park.

The message intercept/decipher capability, however, very nearly got shut down during the development of "Bromide," the cure for *X-Gerät*.

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[60]Using a jammer called *Aspirin.*

The plans for jamming any of these German beam systems depended on utmost secrecy of the knowledge the British had about the beam system to be countered. Revealing the fact that German messages were being deciphered, for example, could reduce the effort to date to meaninglessness, could cause the beam system to change, and could dry up the sources of information, making future beam-jamming very difficult to accomplish. During a routine raid by the RAF on *Würzburg*[61] radars in France, one of the Mosquitoes used for precision bombing went wide, and accidentally made a direct bomb hit on the only *X-Gerät* transmitter on the Cherbourg peninsula, fully 20 miles from the intended bomb drop. The Germans, fearing that some devastating security leak had led to the bombing, made an immediate clean sweep of all procedures relating to *X-Gerät*, including new ciphers. Only the argument that it would set their own program back if they changed the ciphers completely, persuaded the high command to rescind the cipher change order. Bletchley Park personnel would have suffered a corporate heart attack if the change had taken place.

The subsequent jamming of *X-Gerät* was followed, of course, by the German development of *Y-Gerät*,[62] and although, eventually, all beam systems were systematically jammed the Germans continued to use them, with spotty success. Many other systems were rushed into development, such as *Butterblume*[63] (to sense infrared radiation from chimneys, locomotives, etc.), *Ofen* (another infrared sensor to allow aircraft to map the countryside, thus finding the targets), and *Lichtenstein*, the well-known UHF AI (airborne intercept) radar, adapted for mapping for ground target detection, all with but modest success, in 1943.

With the start of systematic night bombing raids, the emphasis, now, on both sides, was on getting a night fighter capability to shoot down the enemy's bombers. This implied some sort of radar which would fit into a fighter aircraft, and this would be tough. In Britain, as in Germany, the radar duplexer was unknown until the Tizard visit to the US, and so two antennas (one for transmitting, and one for receiving) had to be crowded into (or onto) the aircraft.[64] It might seem that an easier task would be to improve the capability to detect and locate bomber aircraft

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[61] *Wurzburg* was a very advanced, 500-MHz (60-centimeter wavelength) radar which could be used to direct searchlights or flak batteries, directly. This radar was discovered in photo-reconnaissance pictures taken by Mosquitoes, and a search for its signals, using American General Radio P-540 receivers, found several such radars, which were immediately attacked by fighter-bombers.

[62] *Y-Gerät* operated on 42-47 MHz, and was otherwise similar to *X-Gerät*.

[63] Hogg, I.V., *German Secret Weapons of World War II*, pp61,62, Arco Publishing Co., New York, 1970.

[64] Germany's *Lichtenstein* airborne radar used a common antenna system for transmitting and receiving, and used a grid-leak-biased superregenerative receiver which was subjected to the full transmitter output pulse voltage. Such receivers require well-insulated detector tubes, able to withstand the enormous bias voltage developed during each transmitted pulse.

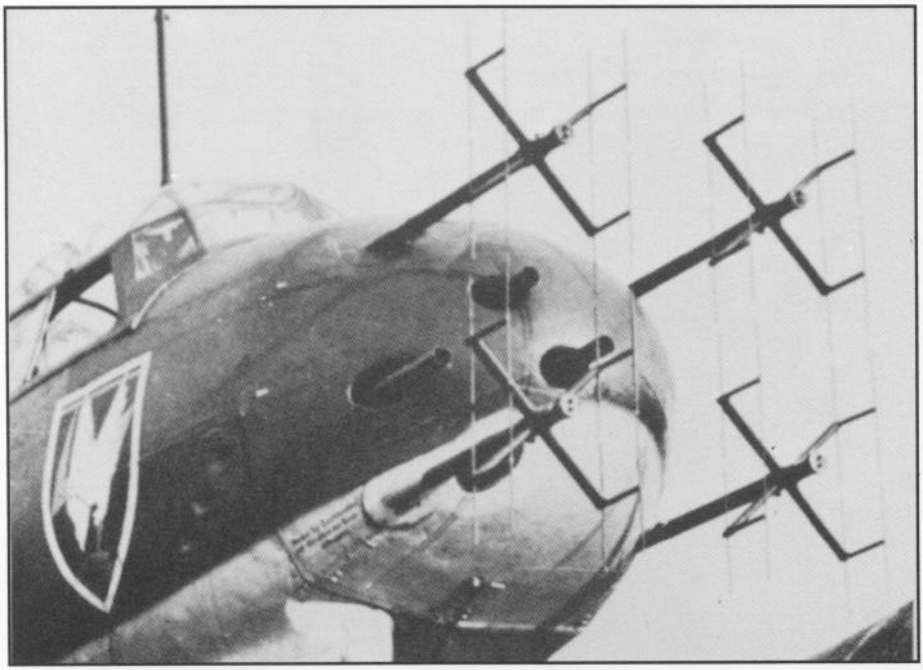

Figure 16. German FuG 202 *Lichtenstein* 400-MHz airborne intercept (AI) radar in nose of a Junkers 88 aircraft. Antennas are four each, four-element arrays of Yagis, and can determine deviation of target from centerline of fuselage, in both azimuth and elevation. Guns showing are 20 mm cannon. (Photo from US Army Air Corps manual.)

with precision from the ground, and then use that data to direct accurate anti-aircraft artillery, or flak. The problem with flak-directing radar is the painstaking aircraft-position-prediction effort required. Against a bomber at 25,000 feet altitude, for example, a high-velocity artillery shell, say, from an 88-millimeter flak gun, takes over 20 seconds to reach the aircraft. In that time, the aircraft, at normal WW2 bomber speeds, flies onward more than three-fourths of a mile. Meanwhile, if the radar is a German *Würzburg*, it can only resolve the aircraft position to about a half-mile, and so, could aim the gun by that much error, at the outset. Coupled with this problem of anticipation of the exact position of the plane after 20 seconds is the estimation of its actual altitude, which affects the timing directly, and the effects of winds. Finally, for reasons which are difficult to understand, the Germans never did master the concept of the proximity fuze. This device is like a small radar in the nose of each artillery shell, which senses the distance to the target and sets off the shell's explosive charge when this distance shrinks to that which is most effective for the type of shell. What the Germans did try,[65] though, was an array of clever

[65]Hogg, I.V., *op cit.*,pp60ff.

Figure 17. Early low-frequency (220 MHz) version of *Lichtenstein* AI radar in Ju 88 aircraft. Antennas are 2-element Yagis (dipole plus passive reflector), arranged for monopulse determination of direction of arrival of echoes, with respect to the aircraft centerline. Cannon for this model Ju 88 were in a pod mounted on the fuselage belly.

"almost proximity fuzes," like acoustic sensors, infra-red sensors, and magnetic detectors, all trying to make the shell explode when near[66] the bomber. With all these problems, there was a continuing emphasis on development of night-fighter aircraft to improve the certainty of downing the night-bombers.

Airborne Radar

The early-warning radar system, Chain Home, was, by the time England had to face the *Luftwaffe*, a growing success. As early as 1940, the thing which worried Dowding, though, was the potential for the *Luftwaffe* to convert to night raids, rather than continuing in broad daylight.

[66]Their lack of an effective proximity fuze was most devastating to their war effort in the case of the V2 weapon. This missile struck the target while traveling at speeds of about 8000 feet per second. As a result, the warhead had already penetrated to a depth of over 50 feet before the contact fuze could set off the main bursting charge. The underground blast formed did far less damage than it would have if the fuze had started the explosion chain about 50 or 60 feet above ground, such as with a proximity fuze.

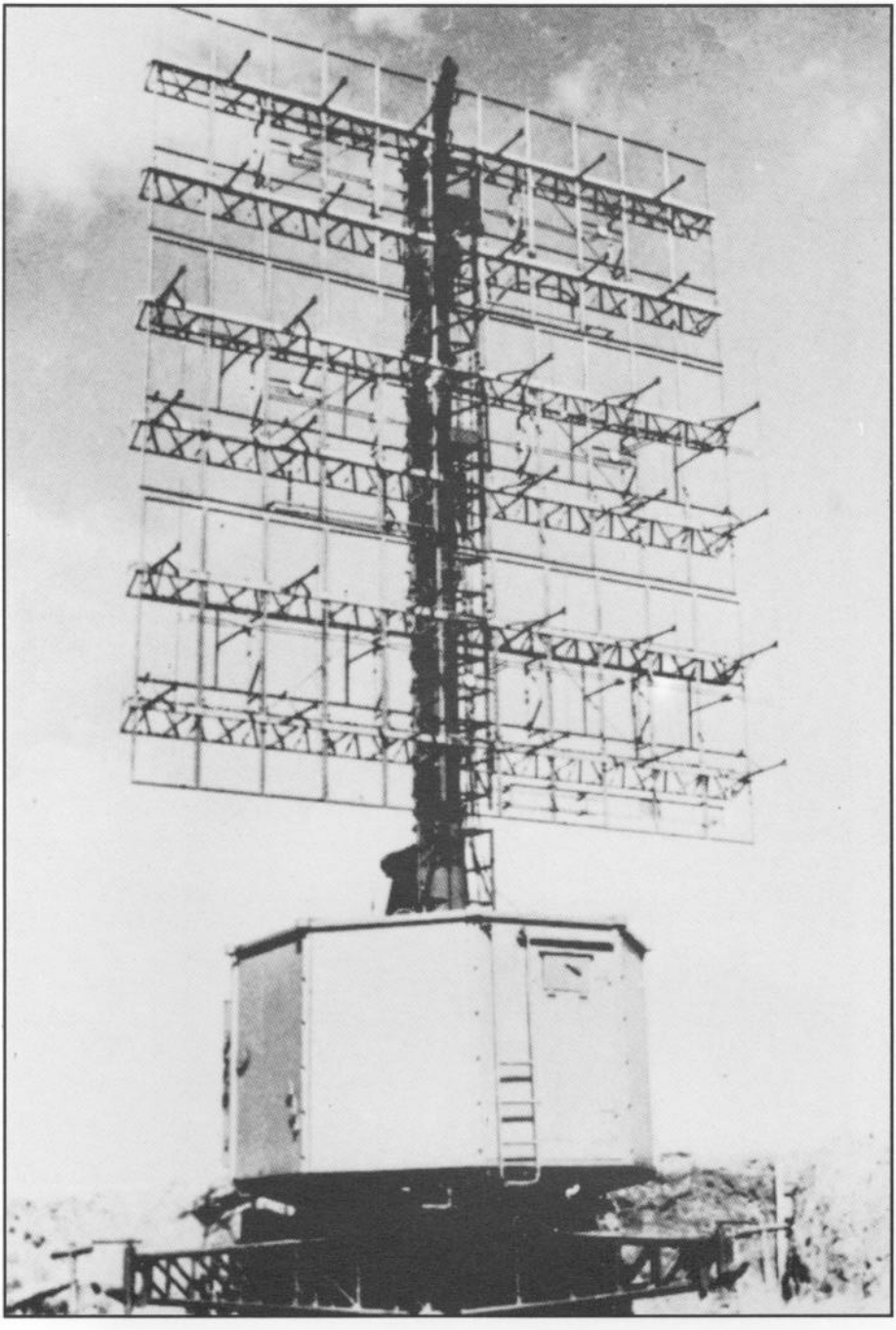

Figure 18. German LZ *Freya* (pole type) radar, which operated at 120-150 MHz. The antenna was divided into a transmitting section (lower frame), a receiving section (middle frame), and the IFF section, on top. This version of *Freya* was intended for air transport, filling five Ju 52 aircraft.

(Photo from bibliography ref. 9.)

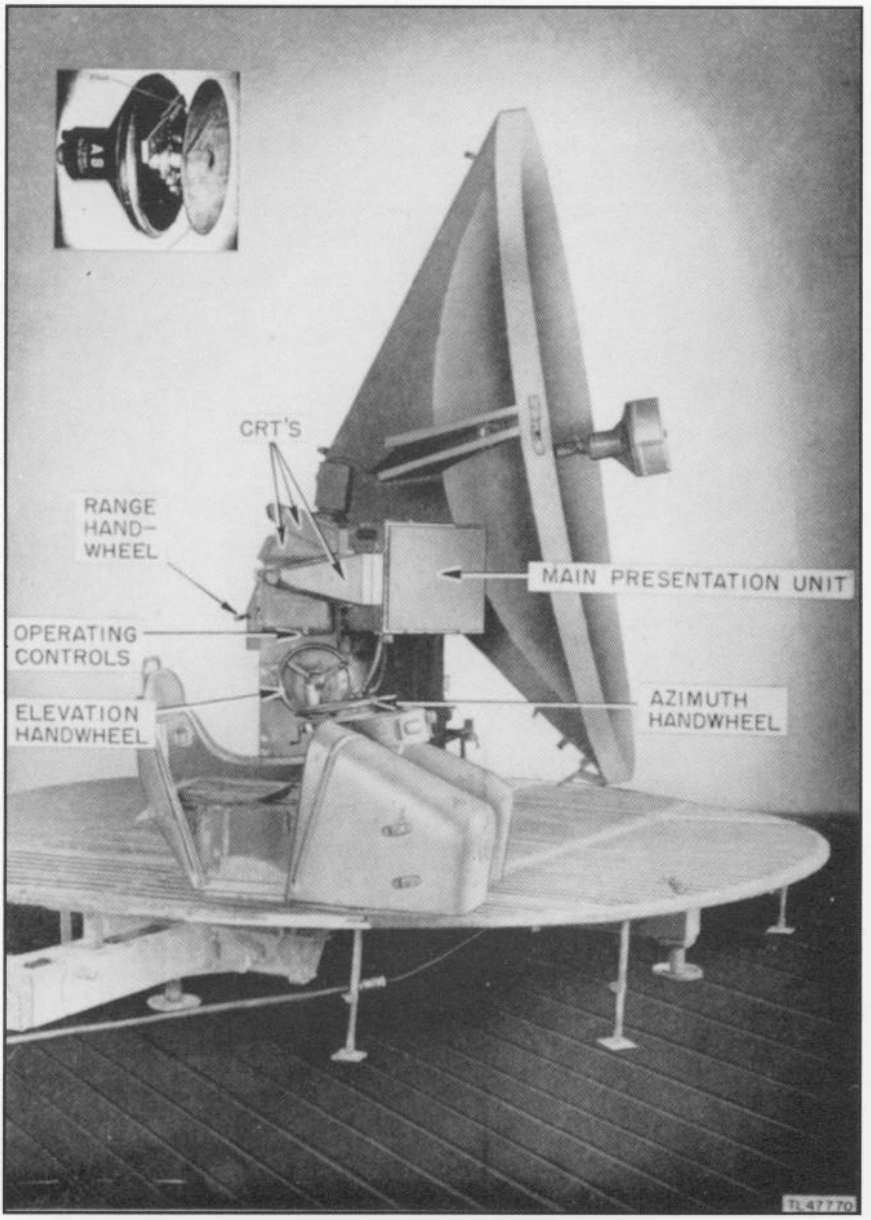

Figure 19. German FMG 39T (D) *Wurzburg* radar, operating at 500 MHz. This set used push-pull triodes as a transmitting power oscillator, and was limited to about 7-kW pulse output power. The original variant, (A), was used as early as 1940 for artillery (flak) aiming. The (D) model depicted was issued in 1942, and had a rotating dipole in the antenna feed projector, shown in the inset. The offset of the dipole from the projector centerline gave the radar a conical scan of its lobe, improving the accuracy of the set for directing flak or searchlight. With its superregenerative receiver, the radar's effectiveness was severely hurt by the Allied use of Chaff or Window. (US Army Signal Corps photo.)

With a good beam-riding system they could hit targets as well at night as during the day. Then although the Chain Home would continue to detect and track the attackers in to their targets, the interceptors would not be able to see to shoot down the bombers. Luckily, R.V. Jones and his colleagues had found the *Knickebein, X-Gerät*, and *Y-Gerät* beams, and had blunted their effectiveness through jamming and spoofing. RAF photoreconnaissance and bombing raids on German targets had disclosed that the Germans, too, had radar, and could, in theory, do to RAF Bomber Command what the Chain Home system had done to the *Luftwaffe*. Meanwhile, the intelligence people, under Jones, had completely dissected the three main types of German radars found. These were:

1. *Freya*, a 125-MHz (2-meter-wavelength, approximately) radar designed for the German Navy by Gema, but commandeered by Goering when it appeared that he might need it before there would be an invasion of England;

2. *Würzburg*, a 500-MHz (60-centimeter wavelength) radar, by Telefunken, but with a parabolic dish for an antenna reflector; this radar, made in four variants, had been designed for the *Luftwaffe*, from the start, for flak-control;

3. *Seetakt*, operating at 350-MHz (1-meter wavelength). Originally designed by Gema, in 1936, for aboard ship, and first seen in 1939 when the pocket battleship *Graf Spee* was scuttled in the Plate River mouth, after having been trapped there by the Royal Navy, this radar became a coast-watcher radar, for anti-shipping.

Now, Jones' scientists were devising countermeasures to reduce the effectiveness of these radars, while the Wimperis staff were trying to stuff a radar into a fighter plane, so as to be able to shoot at enemy planes in the dark. Unknown to Jones, the Germans were also developing an airborne radar able to guide an interceptor to an attacking bomber. This radar was called *Lichtenstein*, and operated at 410-520 MHz. This radar was being fitted in two twin-engine aircraft, the Junkers Ju88 and the Heinkel He219, both very impressive in performance.

Meanwhile, in response to a threat to Britain which was quite apart from the invasion threat, namely the U-boat wolf-packs which were strangling the island nation, RAF Coastal Command planes needed a breakthrough in their effort to stop the U-Boats. The old WW1 tactics of racing to the suspected U-Boat refueling spots, based on radio signals intercept, and using fast destroyers, wouldn't work now. The U-Boats had adopted the *Kurier*[67] signaling system,

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[67] *Kurier* used on-off keying, like Morse, exept that the message, already encrypted, was sent in a burst, at about 100 words per second, on a prearranged frequency, at prearranged times. To a casual listener, a message sounded like a burst of static.

Figure 20. A. Gerald Touch, who was one of the young engineers on the Chain Home project, and later developed the ASV 200-MHz airborne anti-shipping radar. This radar was changed to 400 MHz by Touch's group, and, after the technology exchange with the US, was further changed to 500 MHz and powered by a ring oscillator. German ELINT of the radar's signals prompted the conversion of anti-submarine patrol bombers to microwave radar, like the British H_2S and the US ASG and AN/APS-2.

which was difficult to intercept, and the U-Boats were nearly as fast as the destroyers. Furthermore, German U-Boats were outfitted with very effective anti-aircraft gunnery and their crews were trained to be aggressive against aircraft, and this put in real peril any daylight attacks against them by patrol aircraft. To destroy a U-Boat the bombs dropped had to explode very close to the hull, and, preferably, under water. Without precise bombsights, like the Norden, this required dropping Torpex depth charges, set shallow, from very low altitudes, like 300 feet or so. Unless caught by surprise, the sub could almost guarantee hitting the aircraft during such an attack, often on the run-in, thus ruining the bomb-drop pattern.

Under the leadership of Gerald Touch, a group of the Wimperis staff had succeeded, by September, 1938, in developing a submarine-detecting airborne radar called ASV (air-to-surface-vessel) working initially at 220 MHz (1.5 meters wavelength), but whose antenna beamwidth was far too broad to allow accurate bombing, in the blind. The frequency used was as high as British technology would permit using at the time; by 1940 the ASV had been pushed in the laboratory to 500 MHz, but the power level had dropped. The technology exchange with America would soon change all this, enabling the British to use NRL's ring oscillator to gain significant power boost in these radars.

What the ASV radar was very good at was surprising German submarines. While the U-Boats were recharging batteries on the surface at night, the radar, mounted on a long-range patrol plane like a Wellington, Sunderland, or Liberator, would pick up the sub's echo and allow the pilot to fly straight at the sub. This was accomplished by "lobe-switching," aiming the radar's fat beam to either side[68] of straight-ahead, and then flying along a course which showed the echoes from the U-Boat (or ship) as being exactly equal in size from both lobes. This was far more accurate than trying to maximize the echo in a single beam aimed straight ahead.

When the radar indicated a range of about 2000 yards, the pilot would thumb on a Leigh light, a powerful arc-lamp which would stab a brilliant spear of blue-white light right at the sub. The light was pre-trained by the radar indications, so that its initial illumination was usually directly at the sub. The aircraft's forward gunners would immediately have to get to work, to keep the sub's deck-gun crew off-balance, while Torpex depth charges were rolled out

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[68]The ASV radar had a single transmitting antenna, aimed straight ahead, and two receiving antennas, each off-center-aimed, one left, and one right of center. The radar receiver was switched rapidly back and forth from one receiving antenna to the other. The operator's display was a CRT with the range-to-target marked along the vertical centerline. Echoes showed up as pips sticking out either side of this centerline. The pilot would steer to make the left and right pips equal in size, thus fly directly toward the target causing the echo.

to break her keel. This tactic worked well at night, but in daylight, German U-Boats often scored hits on attacking aircraft before the aircraft got within machine-gun range, and many times the damaged aircraft could not make it all the way back to a safe base. This is why the night attacks, using ASV (and later, ASB) radar and the Leigh light, had to be done with speed, precision, and surprise. Failure of the aircraft gunner to rake the deck thoroughly would invariably lead to successful manning of the deck-mounted heavy machine gun, and possible loss of the aircraft.

The same technique was not feasible for use by interceptors against bombers, because the light would attract too much deadly gunfire from both the bomber under attack and its escorts. The radar alone was far too crude to aim guns, since at these frequencies (~500 MHz) the antenna size which was aerodynamically affordable could not produce a fine, narrow beam for gun-aiming. Nonetheless, the ASV was modified for use by some Mosquitoes and Beaufighters, and the Germans, too, pushed the engineers to install their 500-MHz *Lichtenstein* radar into the nose of an interceptor aircraft. What was really needed for the aircraft interceptor role was a radar having a much shorter wavelength, so that, even with necessarily small (aerodynamically clean) antennas it could produce a thin, powerful beam for gun-aiming. In the labs all over England (and in the other four countries where radar was undergoing development), the problem of shortening the wavelength was under attack.

In Germany, meanwhile, the *Luftwaffe*, now living under Goering's "one-year" rule, in which the only research and development allowed was that which could be brought to the production stage within one year's time, had to go to an airborne radar not unlike the British ASV or American ASB submarine-finding radar. They fitted several adaptable twin-engine planes with the system, a pulse radar operating at 490 MHz, called *Lichtenstein* (and mentioned above). The work-horse Junkers 88, usually a bomber, had the radar placed in the nose, with the array of dipole antennas sticking out in front like four salad forks. These four antennas allowed the use of a sort of "monopulse" technique, in which their outputs were cyclically sampled to allow the pilot to fly such as to equalize the signal pips from all four. This placed the target directly on the fuselage longitudinal axis, ready to be shot at. The Ju88 had 20 mm cannon firing through the antenna array. The twin-engine Messerschmitt 110 was similarly outfitted. These radars permitted German fighter planes to regain some measure of kill capability against RAF night bombing raids, but the same countermeasures used against the German *Würzburg* ground radars, operating at about the same frequency, readily confused the *Liechtenstein,* as well.

In Britain, the search for a way to generate the short wavelength radar signals was coordinated by an inter-service committee headed by Fred

Brundrett. He had been witness to the terribly debilitating interference caused by Lindemann at every step of the development of the longer-wave radars, and so he kept the key development away from Lindemann's Clarendon Laboratory at Oxford.

At the University of Birmingham, two scientists, Henry Boot and John Randall, working for an Australian, Mark Oliphant, revived two American inventions, one old and one new, the magnetron and the klystron, respectively. When news of this work reached Lindemann, he went into his usual rage, and tried to get Churchill to move the work from "those damned colonials with their colonial ideas" to his Oxford labs, but Brundrett's decision was left standing.

The Magnetron and Microwaves

The magnetron was an electron tube devised (and patented) by Albert W. Hull, of GE, back in 1916.[69] He had been striving for a tube which clearly avoided patent interference with deForest's audion. He knew, from basic electromagnetic theory, that magnetic fields could control the flow of electrons in a vacuum tube, in a way which was analogous to the way electric fields applied to the grid structure control the flow in an audion-type tube. So he developed a tube which was a diode having a controllable magnetic field. In the standard GE tradition, derisively referred to as "Greco-Schenectady," the tube got a Greek name: magnetron. (GE also developed, and named, the Pliotron and the Kenotron.) What Hull discovered was that if he split the diode's cylindrical anode into two halves, at a certain magnetic field strength the electron flow between the central cathode and either of the anode halves oscillated, at a frequency determined by the tuning of the anode circuits. Today, we call this mode of magnetron oscillation the cyclotron mode. Hull's invention had gone to the shelf, and was declared no longer necessary, nor practical, once the patent litigation regarding triode tubes had been settled among deForest, AT&T, Marconi, and GE.

Then, during the early and mid-30s, Arthur L. Samuel, a research engineer at Bell Labs, became quite productive, patent-wise, in the field of ultra-high-frequency oscillator tubes. He invented a number of triode arrangements, including the "doorknob" tube and a dual triode with internal tuning circuits (Lecher lines). Then, in 1934 he took Hull's magnetron, and began putting the tuned circuits, sometimes in the form of cavities, inside the tube. One form of his magnetron had four cavities symmetrically spaced around a central cavity which had the cathode in the center. This was the first multicavity anode magnetron.

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[69]US Patent No. 1,387,985.

Samuel's work was largely unknown outside Bell Labs. Mark Oliphant's staff, starting with the Hull-type magnetron, found out that if the split-in-half anode was further split, say into a total of six or eight segments, and if each segment was connected to an ultra-high-frequency tuned circuit, the oscillations became very powerful, as it seemed that the tuned circuits reinforced each other's signal flow. By making the anode segments into carefully-machined cavities, the tube would produce powerful oscillations at frequencies whose wavelengths were set by the dimensions of the cavities, and had little to do with the cathode-to-anode spacing. Small cavities, small wavelengths.

Until this magnetron breakthrough, they had been working on a different tube, a much more recent GE[70] invention, dubbed by GE the klystron, in classic Greco-Schenectady tradition. The klystron operated in an electron-bunching mode, in which the bunched electrons from the cathode blew past a cavity, inducing oscillations in it, much as a police whistle pitch is determined by the size of the whistle cavity, and is initiated by the little pea which tumbles bunched air past the slit in the cavity. In the klystron this cavity had some of the oscillating currents fed back to another cavity, near the cathode, and it was this second cavity which bunched the electrons in the first place. If the two cavities had identical natural frequencies (were the same size), the electron bunching became more pronounced, and the cavity oscillatory currents became moderately strong. Short wavelengths it could get, but somewhat short in power, too, at least for radar transmitters.

The multi-cavity magnetron was clearly the answer to generating very short wavelengths for airborne intercept (AI) radar. While the klystrons of 1940 could produce 10 watts or so, the magnetron could make kilowatts. What has been claimed by the Japanese in recent years, is that they had developed, almost simultaneously with the British, a segmented, multi-cavity magnetron, and, later in the war, had enlarged it to produce hundreds of kilowatts, as their aim was to make a Death Ray generator. Amazingly, the Japanese magnetron very closely resembled the British unit, even to the glass filament seals, the evacuation seal-off tip, the cavity dimensions, and the detailed layout. Both bear a striking resemblance to the drawing in Samuel's patent, except for the specific number of cavities surrounding the cathode.

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[70]GE's W.C. Hahn and G.F. Metcalf claim invention of the device in 1938, but credit is usually given to the Varian brothers for the development of the modern klystron, and Sperry claimed the name to be their trademark.

Tizard, and the Americans

The time period was mid-1940, and the Battle of Britain was underway. Fearing an imminent invasion by German troops, Churchill, who had been kept abreast of the development of all scientific breakthroughs, including this AI radar, decided that a knowledgeable radar scientist ought to take a sample of the latest English developments to America and to Canada, where, he hoped, the fight for saving civilization from Hitler might continue, even if England were overrun. Henry Tizard, who had been arguing for bringing American science and industry into the war before the American government was ready for war, had already sent Professor A.V. Hill to trade, on a *quid pro quo* basis, with American scientists in various fields of weaponry in 1939, but Hill was restricted by security regulations from talking about radar or ASDIC, the British name for sonar. For this new unrestricted mission Tizard himself was chosen, and he packed his valuable treasures, including a working magnetron, for the trip to America aboard the *Duchess of Richmond.* He was accompanied by RAF pilots and radar operators, so as to be able to talk shop with American military and technical people.

Once here, he visited the Naval Research Laboratory[71] where several operational shipboard radars had already been produced, and which were in mass production at several factories, including Western Electric and RCA. Tizard was surprised that the US. even had a radar, let alone several which were already in the fleet. Hoyt Taylor and Robert Page toured Tizard through the labs and onto the roof, where there were four "mattress" array antennas for the several generations of shipboard radar which had been developed at NRL over the past 4 or 5 years. The 500-MHz ring oscillator which was producing 25-kilowatt pulses was demonstrated, along with the old (1937) radar transmitter which had been aboard the *USS Leary* for sea trials, and many pictures showing the stages of development of the Navy radar components. NRL showed Tizard their 500-MHz airborne radar, intended for use as an altimeter in zero-visibility conditions.

Then Tizard showed, then described his 10-cm-wavelength magnetron, which many of the Americans recognized, but which had these puzzling cavities around its anode. Hoyt Taylor surprised the visitor, at this point, by remarking that the *USS Leary* transmitter they had just inspected used a Hull[72] Cyclotron-mode magnetron, also operating, coincidentally, at 10 -cm

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[71]Allison, David K., *New Eye for the Navy: The Origin of Radar at NRL*, NRL Report 8466, pp154ff, USGPO, 1981.

[72]It is a mystery why the Samuel four-cavity magnetron was not further developed by Western Electric or Bell Labs, for it was Western Electric who manufactured the Hull-type magnetron for the *Leary* radar, and it was Bell Labs who later duplicated the Tizard magnetron.

Figure 21. The first 500-MHz ring oscillator, using four Western Electric doorknob tubes invented by Arthur Samuel. The ring oscillator concept was an NRL contribution to VHF/UHF radar. Calendar page showing was for archival reasons. NRL scientists felt they had achieved a breakthrough, and wanted to document their work.

(Photo taken by Leo C. Young; photo courtesy estate of Leo C. Young.)

to 25-cm wavelengths, and producing 30 watts of power.[73] Taylor and the other Navy scientists were frankly dumbfounded at Tizard's claim of 10 kilowatts[74] from his magnetron. They told him they disbelieved his claims for power levels produced, so he asked where they could test it. They took him to Bell Laboratories, where the device could be tested, and where there was a good complement of UHF measuring gear. Tizard's magnetron produced about 8-kilowatt pulses at a frequency of 2900 MHz, or 10-centimeters wavelength. The Americans[75] were convinced.

Tizard took back to England several American circuit advances, including the NRL ring oscillator, which enabled multiple tubes operating at VHF or UHF to have their power levels combined without their internal capacitances combining to reduce the highest frequencies attainable. To obtain high output power at high frequencies has always been a challenge for conventional tube manufacturers. High power implies large size (just to allow

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[73]This radar, first tried on the *USS Leary* in 1937, used continuous-wave modulated signals, rather than pulses. NRL's series of high-power pulse-forming devices wouldn't be available until 1938-39.

[74]Howeth, Capt. L.S. (USN), *History of Communications-Electronics in the US Navy*, USGPO, 1963.

[75]It is unlikely that A.L. Samuel was present for these secret tests of Tizard's magnetron. At this time, Samuel was working on radar duplexers under a Bell Labs contract from the Navy. Immediately after Tizard's visit, though, Samuel was put on the magnetron project.

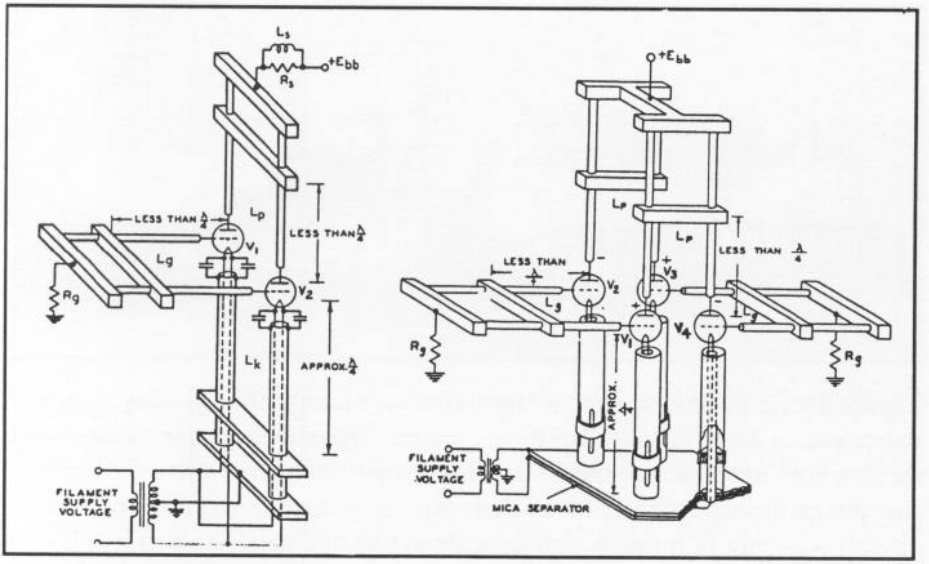

Figure 22. Notional sketches of push-pull UHF oscillator, such as was used in German *Freya* and *Wurzburg* radars, and British H_2S AI radar, and NRL ring oscillator. The ring arrangement could utilize any even number of tubes, and one version of the Signal Corps' SCR-270 was tested with 16 each 100TH-size tubes. The four-tube arrangement pictured would be similar to the transmitter in the Navy ASB-5 radar, operating at 500 MHz, using Eimac 15E tubes. (Drawings from US Army Signal Corps.)

for the dissipation of heat), increased spacing between conductors (to eliminate voltage spark-overs), and heavy conductors (to carry the increased currents). All three of these characteristics, in vacuum tubes, tend to reduce the maximum frequency of operation. The British had obtained the maximum power available from their ASV radar transmitter, a push-pull two-triode affair, and, it operated originally at but 175 MHz, later forced to almost 500-MHz, with different tubes, and at lower power. The Germans also went to the two-tube push-pull circuit in the *Lichtenstein* and *Würzburg* radars. This power problem had limited the effectiveness of the ASV radar in Britain, and had forced the Germans to make up for the low output power of their 500-MHz radar, *Würzburg*, by outfitting it with a huge antenna. This had the advantage of giving good pointing accuracy, but had the severe disadvantage of very poor coverage for search purposes. The ring oscillator allowed an increase in the number of output transmitter tubes used, provided the number was always even. Early in the development of the circuit, NRL scientists had offered the circuit to the Army Signal Corps, who maintained a liaison with NRL throughout the development of radar. This circuit, expanded to 8 or 16 tubes, allowed the SCR-270 radar to extend its maximum range by a factor of two.

Figure 23. Japanese destroyer in Manila harbor a month after V-J day. Note the two horns on the pylon ahead of the mainmast. These are separate transmit and receive horn antennas for their Mk 2 Mod 2 10-centimeter microwave radar, first put on destroyers in 1944. Its detection range against a Corsair or Hellcat aircraft was only 12 miles, which gave about two minutes warning time. It was planned that destroyers equipped with these radars could stand off from critical targets as pickets, but by this time the overwhelming air power of the US Navy made their use irrelevant. This destroyer was in Manila to pick up Japanese POWs for transport back to Japan.

Tizard also showed great interest in the new NRL radar duplexer, which could operate at the 10-cm wavelengths of the British magnetron, and which allowed transmitter and receiver to share the same antenna. All British radar designs, including those using the new magnetron, heretofore had to employ dual antennas[76] to separate transmitting functions from receiving functions. As early as 1936, both US. and British workers in the field had discovered that the only way one could obtain a satisfactory radar receiver sensitivity at frequencies as high as this (3000 MHz, or 10-cm wavelength) was through the use of a superheterodyne circuit, and, furthermore, the only satisfactory heterodyning element in that circuit was the lowly crystal detector, just like Dunwoody used in wireless experiments in 1906. Special crystals were designed for radar work, being very small, and with fixed electrodes. (At least, the operator didn't have to fuss with a cat's-whisker!) These crystals were quite delicate, though, and could be burned out by allowing too much of the radar transmitter power to leak into the receiver.

The first British designs using the 10-cm magnetron had many such crystal burn-outs, sometimes caused by accidentally aiming the radar antenna pair at too close a metal object, like a quonset hut or metal shack nearby. The NRL duplexer cured this problem. It placed a small enclosed spark gap in a

[76]The British called their airborne 10-centimeter wavelength antennas "cheeses", because of their shape, resembling half-circles of what we would recognize as longhorn cheese. Two such cheeses were stacked for a radar.

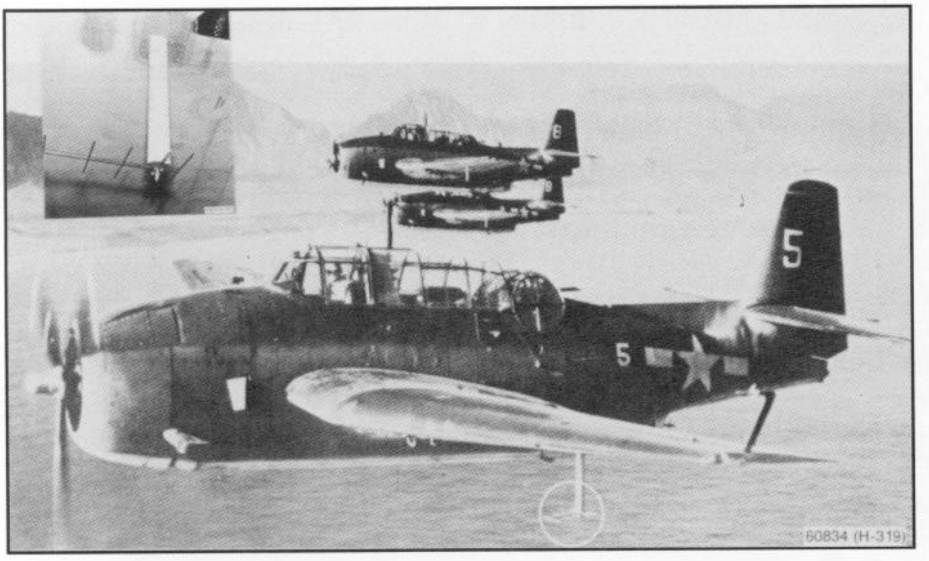

Figure 24. ASB-5 antenna mounted underwing on the TBF aircraft. This radar was the US 500-MHz version of the 200-MHz British ASV. The antennas, one under each wing, pointed either ahead or abeam, depending on whether the aircraft was engaged in a bombing run-in or a search, respectively. (NRL photo.)

strategic spot in an arm of the transmission line from transmitter to antenna. When the transmitter emitted its powerful pulse of energy the spark gap fired, shorting that arm of the line, and protecting the receiver. Many of the improvements in duplexer designs came, later, from the same A. L. Samuel, of Bell Labs.

The Americans ended up able to reproduce the magnetron and then improve it, in a few days' time. Within a few months, Bell Labs, supported by a conglomerate of scientists who would be forming the MIT Radiation Laboratory, had made up an entire 10-cm radar. In a year, they had made a 3-cm radar for airborne use. NRL took the plans for the British ASV radar, immediately saw the similarity, except for frequency, with their altimeter, and married the two designs. They put a 4-tube ring oscillator in the transmitter circuit, using new Eimac 15E tubes, and thus made a superb 515-MHz anti-sub radar, the ASB, which was mass produced (26,000 units) in the war by Sperry, Western Electric, and Westinghouse. The British and Americans were each surprised to find that the other had been developing proximity fuzes. And both sides had achieved some success. With their efforts combined, Carnegie Institution's stumbling-blocks in fuze development disappeared, as did those encountered by the British. Another item on the table was the famed bombsight, developed by Karl Norden and made by Sperry, Kollsman, and Bendix. Britain wanted it, and the Americans wanted the cavity magnetron.

Meanwhile, back in Britain, while the RAF fighters were whittling away at the *Luftwaffe* in daylight attacks, a turf battle between Coastal Command, Fighter Command, and Bomber Command began, regarding the use of the new airborne magnetron-powered radar being developed by the group soon to be known as, simply, TRE. The letters represented Telecommunications Research Establishment, but that name was secret, so the locals around Worth Matravers, Swanage, and Leeson House, where the organization was housed from time to time, thought it meant "Traveling Round England." The radar was dubbed the H_2S, which some claim derived from "Home Sweet Home," and Coastal Command, who flew against shipping and subs, thought the safest use for such an invention would be aboard their Sunderlands, Liberators, and Wellingtons. Any of these craft which got shot down wound up several thousand fathoms down, far from German scrutiny, whereas, if used in Bomber Command's aircraft on the continent, any aircraft losses were tantamount to compromises of the whole notion of centimeter-wavelength radar. Fighter Command, of course, wanted the H_2S for their bomber interceptor planes.

For use in intercepting bombers, though, a large problem cropped up. Any fighter that had to compete with the fast twin-engine German bombers like the Heinkel 111 had to be fast, itself, as well as maneuverable, yet roomy enough for the H_2S radar. With the original British two-antenna design, this radar took up considerable space in any aircraft. So the problem of which aircraft would be outfitted with H_2S came up. It wouldn't fit on a Hurricane or Spit, and seemed better suited on a twin engine plane having a vacant fuselage nose section. The Bristol Blenheim, a light bomber, was tried and worked well, but was too slow and too sluggish to maneuver. A similar plane, made much lighter but with bigger engines[77], was the Beaufighter. After a shaky start, owing to the plane's enormous engine power (and torque) and hard landing characteristics, it eventually worked quite well, being fitted with the single-antenna (with duplexer) and armed with a four-cannon gun-pod on its belly. These guns fired 20 millimeter explosive rounds, packed in 60 -pound canisters, and so could fire for perhaps six to eight seconds, then had to be reloaded. Such use of large-caliber cannon rather than the well-established British .303 was carefully considered. The British were impressed with the damage that a single hit from a Bf109's 20 mm cannon could do, but liked the dozens of nasty little holes that their Spits' eight .303s could make. They decided on very short bursts of fire, to maintain secrecy of the interceptor's position, and therefore chose the 20 mm cannon.

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[77]The Beaufighter used Bristol radial engines having sleeve valves (like the old American Franklin automobile). This valving gave the engines a smooth roaring sound unlike the staccato of poppet-valve engines.

Once the pilots learned to trust ground control radar operators to get them positioned properly for a lead-pursuit[78] course onto the bomber's track, and to trust the H_2S operator to bring them right in under the tail of a bomber, they became very effective, but it took nerve to trust a radar to bring the huge Beaufighter to within 300 yards of a Heinkel in the black of night. Once the pilot got this close, he could usually just make out the huge dark form of the bomber visually, directly ahead. After making any needed minor corrections, he would thumb the red teat on the control stick, and the entire plane shook and shuddered with the explosions from the four cannons. No matter how well the two-man crew braced themselves for the gunfire, it always startled them, nearly to death. The H_2S operator, especially, had to be sure he wasn't peering too intently into the radar scope, because of the virtual guarantee of him banging his face into the scope shroud when the guns went off.

The bomber was often cut in two by these bursts, for, if the Beaufighter had made the recommended approach, from below and behind, the target's wing root fuel tanks and main wing spar were disintegrated by the burst of cannon fire, with the wings often gracefully folding up together, and the Beau was then showered by bits and pieces of the bomber. The tough job was then for the H_2S operator to slip down into the aircraft belly and manhandle new 20 mm cartridge canisters onto the cannons, while the pilot maneuvered for the next quarry. These operators suffered many broken bones and smashed and dislocated fingers in this task.

The Germans reasoned that there just had to be a new radar aboard these British night-fighters, but they could not detect any emissions from them. Telefunken and Lorenz worked around the clock trying to make receivers which could detect the radar emissions, but the hard part was getting the experimental receivers safely to England, then exposing them to a Beaufighter, and getting safely home again. Many of these ferreting flights never returned, as they looked to an H_2S just like a harassing German bomber, and were summarily exploded in flight by the Beaus. Some did return, and their *Magnetofon* tapes were scrutinized for telltale emissions by the Telefunken and Lorenz engineers; finding none, they convinced themselves, then the *Luftwaffe,* that the Brits must be using a form of infrared interceptor-directing. They concluded that the British night-fighters homed on the heat given off by the German bombers' engines or exhaust. Again, it was a case where the Germans found it easy to believe in infra-red detection, because that was their own main channel of research into night-intercept of Allied bombers.

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[78]The interceptor is directed around to the rear quarter of the bomber, and it then flies a course in which the range to the bomber (as indicated by the radar) is shortening, but the bearing to the bomber (angle off the interceptor's nose) is held constant. The result is a smooth curve which brings the interceptor directly behind the bomber.

Ironically, Lindemann (Britain's Lord Cherwell), Churchill's favorite all-around science advisor, had long advocated infra-red techniques rather than radar, even though all earlier tests of such systems by British, German, and American organizations found them to fail in smoke, fog, and clouds. His bias toward infra-red methods might have leaked to German agents in Britain, which would have helped the Germans believe that the Beaufighter used infra-red techniques. To thwart this suspected method of detection of the German bombers, the German decision was to outfit some planes' engines with infra-red absorbers and dissipation devices so that they wouldn't emit enough of the nasty radiation to be detected. To counter possible British infra-red night fighter seekers/aimers, the Germans flew several bombing missions using Junkers 88 bombers, having slipstream-cooled doubled engine shrouds and exhaust mufflers to reduce the infrared emission. The results were disastrous, for the thick shrouds only made the bombers slower, and easier for the Beaus to shoot down.

Rotterdam: the Wake-up Call

The H_2S and its all-services American cousin, the AN/APS-2, became quite plentiful, and still they were used cautiously. Originally used only on Mosquitoes and Beaufighters flying over Britain, they were allowed to be used in anti-submarine warfare somewhat later, and, finally, in many bombers as well. NRL's PPI display was the key to bomber utility, once it had been modified for sector-scan, meaning that it displayed a piece-of-pie-shaped map as the radar antenna nodded from side to side in the radar nacelle or nose of the aircraft. This gave the bombardier a map-like display showing ground targets not unlike an aerial photograph.[79] After the RAF had enjoyed several months of using the H_2S in all three roles, finally, in January, 1943, a Short Stirling bomber, outfitted with H_2S as a ground-mapping bombing aid, was shot down in an RAF raid on Rotterdam, and it didn't get too badly banged up in the crash. The H_2S was recovered by the Germans, and the magnetron was found to be in operating condition.

On finding the magnetron and the 10-cm waveguides, the Germans were stunned. They had never conceived of using such wavelengths. Their first task was to find a way of receiving these signals, so as to allow their own planes to identify and evade the British planes that used H_2S. They were lucky, here, also. In a wrecked Liberator, in late 1942, the Germans had found a partially-intact General Radio P-540-series receiver, having a P3 tuner in it

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[79]Nickname for the US Army Air Corps version of this microwave radar, adapted for blind bombing, was "Mickey" [Dunlap, Orrin C., *op cit*, p134].

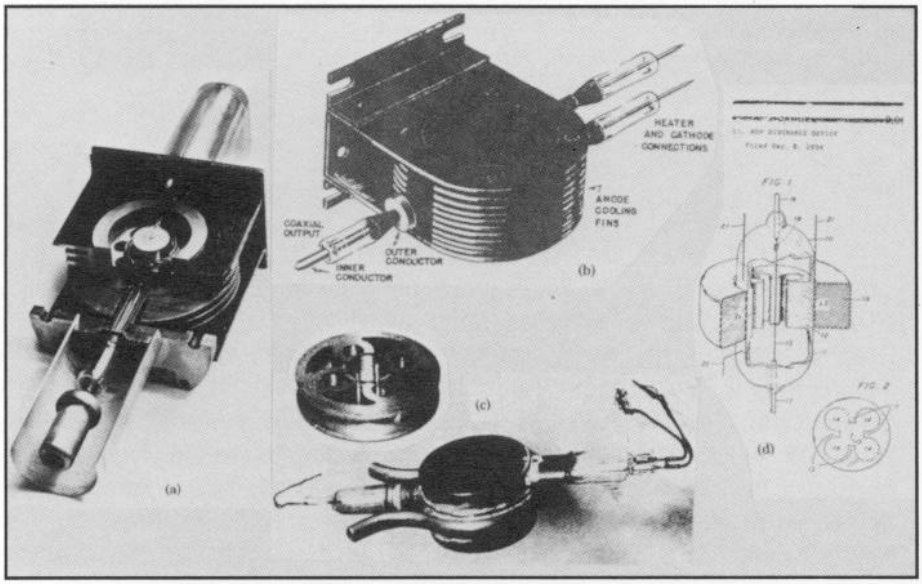

Figure 25. Magnetrons from different nations: (a) British 3-centimeter unit of 1943; (b) US 3-centimeter wavelength unit of 1943; (c) Japanese 10-centimeter magnetron claimed to be from 1942, with detail of cavity-type anode in inset; (d) drawing of a multicavity magnetron copied from Arthur Samuel's 1935 magnetron patent.

covering the range of 1000 to 3000 MHz, or 30-cm to 10-cm wavelength. Until now, they thought the tuner was a clever piece of propaganda, designed to send German science off into a wasteful search for signals in the void of 3000 MHz. Now, the H_2S radar and its magnetron proved that the tuner was not propaganda, but evidence that the Allies could afford the luxury of searching for German radar signals at microwave frequencies before any such signals had even been imagined by the Germans! It demonstrated that the Allies routinely practiced systematic prophylactic efforts to search out new enemy signals at the first appearance of such signals. At last the Germans began to understand just how the Allies could have developed jammers and the many other effective countermeasures so quickly after initial use of any German innovation. Of course, the Germans found it incomprehensible that the Allies would have a powerful technological organization devoted entirely to countermeasures, as well.

Meanwhile, in America, the magnetron was being put to good use. Its earliest operational home was in the Naval airborne radar called the ASG, operating at 3000 MHz. This radar was a natural follow-on to the ASB, the 515-MHz set used in Catalinas, TBFs, and TBMs. When, in 1942, the Army Air Corps adopted the ASG for use in patrol craft and bombers, it was

redesignated the AN/APS-2, and was made by Philco. As the Navy made further reductions in its wavelength, size, and weight, it became the ASD, built by Sperry Gyroscope Co., and fitted into the Navy's PB4Y[80] patrol bomber. This radar operated at X-band (10,000 MHz, or 3-centimeter wavelength), and was designated the AN/APS-3 when the Air Corps began to use it. For carrier-based aircraft it was further reduced in size and weight, and the antenna was mounted in a streamlined under-wing nacelle. This radar was the Navy type ASH, later called the AN/APS-4. It was used on TBM (or TBF, both Avengers) and F6F (Hellcat) single-engine aircraft, the latter of which worked up 20:1 to 40:1 kill ratios against Japanese aircraft later in the war, in night encounters. Early in the war, the Air Corps had a special plane developed for night interception, the P-61 Black Widow, with its SCR-720 radar. By 1943 it was outfitted with the newer AN/APS-4 radar. Within a year, however, squadrons of Navy F6Fs replaced the Air Corps P-61s in the Pacific, as the P-61s had spawned just too many gadgets to continue to perform adequately against Zekes and Bettys, and as the Japanese planes retreated to a war specifically directed against Navy carriers.

But one of the best overall systems to have been designed around the magnetron was the Army's SCR-584 trailer-mounted radar. It was used for search, flak control, artillery control, and ground-controlled intercept. Over 50 of these fine radars were sent to the Soviets, and they found good use in England in fire control against the V-1 Buzz Bombs. In this latter role, the SCR-584 radar plus its M-9 fire-control computer and automatic 90-mm flak gun, rushed to England upon Churchill's personal request, knocked down over 65% of the V-1s which made it to England.[81] This radar was designed by the Signal Corps and MIT Radiation Laboratory, and was produced by Westinghouse[82] and GE in 1943-45.

Countermeasures

When the Germans had recovered their composure after finding the English operating 10-cm radars and the Americans operating ferreting aircraft equipped to detect possible German 10-cm signals, they put highest priority on duplicating the General Radio tuner and receiver, so they could detect when their aircraft were being tracked by these radars. The tuner was used as a basis, by Telefunken, to construct a superheterodyne 10-cm receiver. For the local oscillator they used a klystron, and as a heterodyne mixer, a sealed silicon

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[80]A single-fin Navy version of the famed B-24 Liberator.

[81]Thompson, G.R. and D.R. Harris, *op cit*, pp478ff.

[82]Westinghouse and the Historical Electronics Museum has restored an SCR-584 to original working condition, and it is on display at the Museum, located on Elkridge Landing Road near BWI airport.

crystal unit sufficed. The receiver didn't need much sensitivity; all it had to be able to receive was a powerful H_2S radar transmission. These receivers, called Biscay Cross, were put aboard special Messerschmitt interceptors and in the tails of bombers, and were rushed to U-Boat Command, whose fleets had earlier been devastated by the ASV and the American ASB radar, the Leigh light, and surprise depth charge attacks.

The U-Boat fleet adapted to the British ASV-equipped aircraft attacks upon detecting their 170-180 MHz signals on their Lorenz intercept receivers. The Allies immediately shifted to the American ASB-5 radar and the British ASV Mark II, both operating near 500 MHz. In due course the same fate befell the Allies operating these radars, through the chance intercept by a German ship of these higher-frequency signals. The properly-equipped U-Boat would crash-dive as soon as the signals were heard on their special receivers. These receivers had to be replaced each time the Allies changed over to a new radar frequency. However, Doenitz's forces had most recently been falling prey to an "unknown" radar whose emissions couldn't be detected. This new radar, which was the H_2S in British patrol planes, and the ASH or AN/APS-2 in American patrols, was so accurate that it didn't need a Leigh light. The U-Boats were suddenly being bombed from out of a black sky. Then, as a final insult, American patrol craft using the latest, AN/APS-3 (or -4) 3-cm radar could find U-Boats while they were battery-charging when all they exposed was their new *Schnorkel.*

Thus, relatives of the resilient H_2S had been adapted for airborne interceptor duty aboard the Beaufighter, for precision mapping for night bombing aboard Mosquitoes, Lancasters and Stirlings, and for U-Boat patrol, aboard Sunderlands, Liberators, and Wellingtons. As predicted by Coastal Command, the use of H_2S in raids over Germany was eventually going to lead to the loss of one of the precious radars to the Germans. The free lunch was over.

Aside from building a homing receiver which could detect the H_2S radar emissions, the Germans began cutting aluminum foil "chaff"[83] to the proper lengths to act as decoy reflectors for the H_2S. In addition, they began a crash effort to duplicate the radar. They named this radar *Rotterdam*, after the town where they found the Stirling. But it was far too late in the war, and *Rotterdam* found little use. The most significant outcome of the German discovery of British 10-cm radar, though, was the immediate cancellation of Goering's one-year research limitation order. A more ambitious effort was expended by Telefunken, using the new magnetron. By January, 1945, they had developed a complex of two radars, operating in the 10-cm wavelength

[83]Which they called *Düppel.*

band, one to search for Allied bombers, and one to aim flak batteries. The system was called *Egerland*, with the two radar units called *Kalmbach* and *Marbach*.[84] The automation of flak batteries through the use of Marbach as the aiming subsystem was effective only for a few weeks, that is, until the Allies began using countermeasures, including Window and barrage jamming. After that, the flak batteries were all but useless, as their manually-operated training mechanism had been removed in favor of the radar control.[85]

The foil strips, called *Düppel*, were identical to the British radar-jamming foil pieces called Window. Americans also had developed the same jamming material, which they called Chaff. Released in huge clouds from aircraft, the little strips would fall slowly, and offer an enormous fuzzy echo for the radars to see. The object was to have aircraft fly above the *Düppel* unobserved by the enemy's ground-based radars. The ironic thing is the fact that the three major combatants in western Europe, Britain, Germany, and America, having developed Window, *Düppel,* and Chaff, respectively, each decided to refrain from using it. In all three countries the technique was developed in tight secrecy, and the use of the foil strips over enemy territory would certainly have compromised its secrecy, because the idea would have been so easily copied by the enemy. The really astonishing thing about Germany's thorough military security surrounding *Düppel* was that the German radar designers didn't even know about it, so that when the allies finally used Window and Chaff it paralyzed German radar for a long time. The allies, at least, had been ready for Chaff or Window, on the giving or receiving end.

Many British and American radars had, waiting in the wings, Moving Target Indication (MTI), a scheme in which the echoes from one radar pulse are coherently subtracted from those of the previous pulse, with all pulses working in pairs this way. For moving radar targets, such as aircraft, the target motion makes the target echoes for the two successive pulses slightly different in timing (electrical phase) with respect to each other. The subtraction process, performed coherently, therefore, yields an echo residue representing the features of the two echoes which were not identical. On the other hand, echoes from the Window strips, as they floated slowly in the breeze, would be virtually identical, pulse-to-pulse, and the subtraction circuit would yield no residual echo. The radar, then, would be far more sensitive to fast-moving targets than to slowly drifting foil strips.

Eventually, by late 1944, the Germans fixed the Window problem by utilizing a two-color radar display tube, or CRT. The first color, blue, came from the initial "hit" or echo, and this color phosphor was of very short most

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[84]Hogg, I. *op cit.*, p56.

[85]Price, Alfred, op cit, Appendix D.

persistence. Much more persistent was the second-color phosphor on the screen, orange or yellow. It glowed steadily, not flashing as the cathode-ray beam passed over it. Thus, all echoes, whether from moving aircraft or Window foil strips, showed as yellow blobs, but those from moving objects, like aircraft, had a thin blue outline flickering at their edges, indicating the direction in which the aircraft was traveling.

But the little H_2S receiver which Telefunken made for intercepting the AI radar emissions, even though it wasn't ready until late in 1943, saved many German pathfinder crews from Beaufighter cannon shells. A small tail-mounted antenna fed the receiver, and its output was a simple yellow light. When the light flickered it meant that the plane was being illuminated by an H_2S. At a certain steady brilliance, it meant that the interceptor was close enough that its H_2S was likely to be observing the plane. It was then that the German pilot would dive wildly for the deck, hoping to draw the Beau down into the ground, or at least lose his own plane echo in the ground backscatter or clutter. Later, the warning receiver was connected to a tail gun, whose firing would scare off the Beau. British and American bombers had already been outfitted with warning receivers set to the frequencies of German *Lichtenstein* airborne intercept radars.

The Situation at War's End

The British sincerely felt that theirs was a last-ditch struggle for survival in the 1939-1941 period. Both from the air and from under the sea their national capability to survive was being challenged, and they had their complete scientific attention focused on the means of sustaining themselves. The answer, in their minds, was radar: as a means of predicting the paths of German bombers, so as to intercept them efficiently, and as a way of defeating the U-Boat menace, which was strangling the island nation by interdicting its supplies.

The British scientists actually made two major radar breakthroughs. The first was their development of a 175-MHz (later pushed to 500-MHz, or 60-centimeters wavelength) radar, the ASV, which severely hurt the U-Boat wolf-packs. The second was their development of the multi-cavity magnetron, which enabled the design of the first effective air-to-air fire control radar, the H_2S. While the Battle of Britain was won with the irreplaceable help of a third British radar, the Chain Home 26-MHz (12-meter wavelength) system, this system was technologically inferior to the American Navy CXAM radar, the German *Würzburg*, or to the Army's SCR-268 or SCR-270, all of which were in use in the same time frame (1937-1939). In defense of the British decision to continue to field and use the Chain Home system, though, it proved to be very hard to destroy by bombing, being spread over dozens of acres, and

comprising tall, open-lattice towers and replaceable wooden huts. And, luckily, the Germans never appreciated the importance of the Chain Home system in the systematic defeat of the *Luftwaffe* by the radar-directed RAF fighters. This oversight was contributed to by the basic quirk of human nature which concentrates one's attention on those technologies of one's enemy which most closely mirror one's own. Since the Chain Home radar operated at such a low frequency, it was not readily recognized as being a useful adjunct to British Fighter Command activities. Had the radar operated at the frequencies of the German *Freya* system, it would have physically resembled the American SCR-268 or SCR-270, and the British radar would have been targeted more frequently by the *Luftwaffe*. In addition, the Germans were mislead by several flawed-signals intercept efforts (like those of the *Graf Zeppelin*), and by the effective control held by British intelligence over many of the German agents in Britain.

Undoubtedly, the sharing of radar secrets among Britain, America, and Canada contributed significantly to the remarkable performance of Allied radar and radar countermeasures during the war. The organization, in February, 1942, of all American radar countermeasures under one head, Dr. Fred Terman of Stanford, played a major role in getting ideas efficiently from the field to the factory and back into the field again. This group was the Radar Research Laboratory (RRL), a part of the National Defense Research Committee, who created the MIT Radiation Laboratory, as well. One of the methods used by RRL to get the design engineers intimately familiar with the real-world problems faced by the military people who had to confront a clever enemy was to send the engineers into the battle theater to gain first-hand experience. Some of these engineers had been recruited from colleges and universities, but some of the best came from industry.

The RRL group cooperated with other labs around the country, especially the Aircraft Radio Laboratory (ARL, in which was also located the Signal Corps' ferret aircraft design center), at Wright Field (Dayton, OH), and Naval Research Laboratory (NRL) at Anacostia, DC. They had access to most of the premier electronics companies in the country, and quickly recognized the fine work at General Radio (GR), for example, as a source of basic designs for ferreting receivers. The GR Model P-540 receiver with its various tuning heads became the basis for an entire family of countermeasures receivers, mostly used aboard ship and aircraft. This receiver was designed by GR's Dr. Donald Sinclair,[86] who became one of the senior technical observers in the North African theater upon America's entry into the war. There were hundreds of such civilians, all in uniform, serving in the war, assisting in the optimum application of the newest electronics to the war effort, and feeding

[86]Price, Alfred, *op cit, pp71ff.*

back valuable information about shortcomings and new requirements. They reported to RRL, even though they worked for contractors like GR. Interestingly, Sinclair was rotated back to Britain after serving in Africa, and he was replaced by Richard Raymond. On his return to the 'states, Raymond worked radio signal ferreting problems at ARL with two scientists named Haller and Brown. After the war, Haller, Raymond, and Brown formed the company now known as HRB Singer[87], while Sinclair went on to become GR's Chairman of the Board.

Another advantage the RRL group had over more conventional problem-solving organizations was that they did not have to abide strictly by the "low-bidder" rules and all the time-consuming competition rules. Here they hid behind the military secrecy laws, claiming that wide promulgation of their activities, through the issuance of procurement paperwork, would compromise the secrecy of radar and their anti-radar equipment. They engaged in making their own equipment, if they could, through a ghost company made up of their best technicians and shop-people, called the Research Construction Company (RCCo).[88] When the work volume exceeded what the crash-response RCCo could handle, contracts were quickly let to industries "in the know," often referred to as "RRL camp-followers." Once a good contractor was found, that company got many jobs, mostly without competition. But, on the other hand, the company's work had to be excellent, or out they went, without warning. For some reason, Delco was chosen to design and manufacture some of the early countermeasure sets developed by RRL, and once "brought into the fold" Delco became a favorite quick-response contractor for radar countermeasure equipment. To handle the delicate security issues in their manufacturing plants, Delco openly referred to their equipment as "Anti-Radars," the idea being that nobody outside the official circles knew what the meaning of "radar" was anyway.

The centralization of radar countermeasures in this group speeded the effort of getting a field problem solved, and by the best-qualified individuals. With no such counterpart laboratory, the Axis nations were forced to work such problems as countermeasures and counter-countermeasures in competing small shops which were simultaneously being harassed by bombing. Their remedies were always too little, too late. The use of Window (or Chaff) plus the many forms of active jamming, all developed by this group, proved too much for the German or Japanese radars to handle.

As an illustration of the speed with which Allied scientists could react to a new enemy electronic threat, the case of the *Fritz-X* radio-guided bomb can

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[87]Price, Alfred, *op cit*,p75.

[88]Thompson, G.R. and Dixie Harris, *United States Army in World War II, The History of the Signal Corps, Part 3 - The Outcome*, p302, USGPO, 1966.

be described. In mid-1943, two guided bombs began to be used by the Germans, the *Fritz-X* and the Henschel 293. The *Fritz-X* was simply a gravity bomb, of 3000 pounds weight, with tail fins which could be moved by a servo system controlled by the bomb's radio receiver. A launch plane contained a bomb-flight controller, who remotely controlled the fins on the *Fritz-X* bomb by means of a little joystick which controlled the signals being transmitted to the bomb on a frequency somewhere between 48 and 50 MHz. The Henschel 293 was shaped like a small airplane, with a rocket motor, which propelled it to nearly 400 mph, from which point it was guided by a skilled pilot operating a set of controls in the launch plane. It flew in a controlled glide to its target, usually a ship.

After a preliminary application of the Henschel 293 against British corvettes, with one of the anti-sub vessels sunk, serious use of both began in September, 1943. A flotilla of Italian ships, enroute to Malta to surrender to the Allies, was caught by Dornier 217 bombers, which had been outfitted with *Fritz-X* bombs and a controller's console. Ten to twelve *Fritz-X* bombs were dropped, overall, and sank the battleship *Roma* while damaging the other battleship, *Italia*. Smaller ships suffered near-misses, with casualties from shrapnel. Later in the same week, the Dorniers returned to Italy, where the Allies were invading Salerno. Just offshore, *Fritz-X* bombs hit a British battleship and cruiser and the cruiser *USS Savannah*, exploding in her ammunition magazine handling room, killing almost 300 sailors. Air Corps fighters drove off the Dorniers for the balance of the invasion, but the Navy felt their ships to be in peril.

So the problem of countering the guided bombs was flashed from the Mediterranean fleet to RRL, and from there to NRL, where it received the highest priority, AAA1, which meant working 24 hours a day until it was solved. Having been told only that the bombs were radio-guided in the VHF range, based only on the remnants of a wrecked, unexploded bomb, NRL immediately reworked Hallicrafters S-27 and S-36 receivers to add motorized tuning and a panoramic display, to seek the frequency on which the bombs were receiving signals. For jamming transmitters, which would be used to transmit confusion signals to the bombs once the receivers indicated the proper frequency to jam, NRL scientists had to take a multi-band approach in order to keep the transmitted power from being diluted through being spread over too much frequency spectrum. Within four weeks, NRL had placed five of these jammers and two search receivers (which we would call ESM, or Electronic Support Measures, today) aboard two destroyers, which then raced back across the Atlantic and into the Mediterranean, where they went to work against a raid by Do 217s against an Allied task force just off Algiers. They began signal-searching and jamming as soon as they saw bombs beginning to fall. A total of 25 *Fritz-X* bombs were dropped, and the destroyers could cover only five of the operating frequencies. They noticed that nearly all the bombs

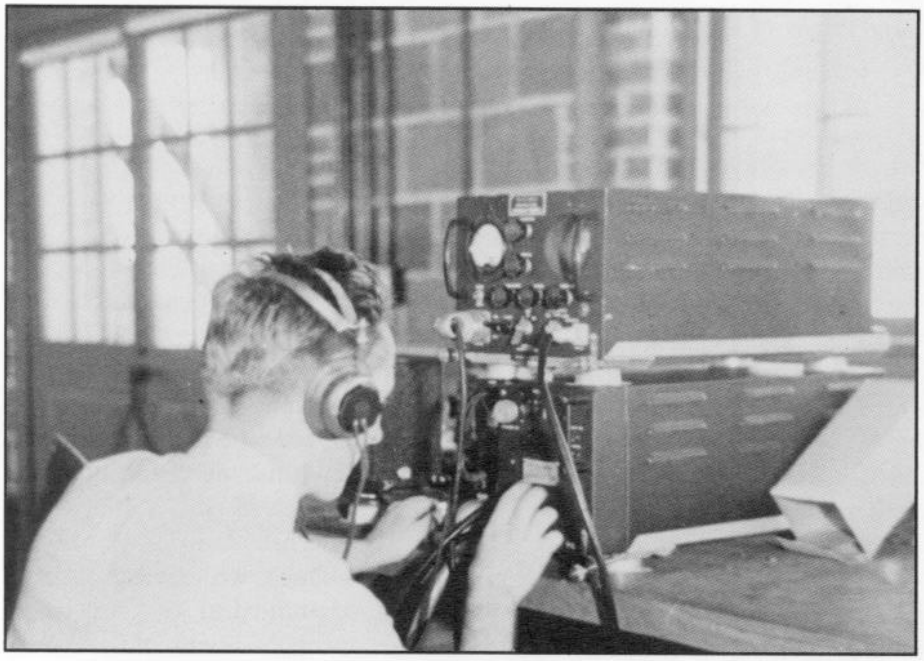

Figure 26. NRL technician testing a new intercept receiver based on the General Radio P-540 on lab bench prior to installation in Navy Catalina aircraft, 1941. (Photo courtesy estate of Leo C. Young.)

veered wide of the convoy, allowing only one bomb to hit a troopship (resulting, unfortunately, in heavy casualties). The jamming is credited with preventing more serious loss. The point is that the Allies really did have a quick-reaction capability in the area of anti-radio and anti-radar devices.

In the Pacific, the RRL effort was translated into direct action by the two services affected, the US Navy and the Signal Corps. In the development of radar systems the Navy and Army Air Corps worked together, effectively shunting aside the Signal Corps work, which seemed pedantic to them. The problem was that the Air Corps and the Navy had mobility in mind while the Signal Corps had to serve the infantry and artillery, as well, with fixed installations. Nonetheless, when it came to crash-development of listening and analysis equipment to learn how to jam and confuse Japanese radars, the job was left to the Signal Corps and their ferret aircraft.[89] These were special B-24Js which carried a few machine guns (a token effort at self-defense) and tons of receivers and recorders. The Corps had learned much from their liaison with RRL, and flew missions deep behind the Japanese lines and over Japan proper, to collect radar emissions from Japanese systems which might be in

[89]Thompson, G.R. and Dixie Harris, *op cit, p318.*

early stages of research and development[90] or were used in troop training, thus gaining valuable time to develop counter strategies and jammers.

This is not to say that RRL's efforts, even cooperating with the Brits' Signals Establishment, were always successful. The German V-weapons were originally thought to be radio- or radar-guided. The fact that signals for this purpose had never been detected by the Allies was tossed aside. After all, hadn't the Germans been ignorant of the very possibility of 10-cm radar signals for two full years? A tremendous effort at searching for the guidance signals was launched, coupled with a shotgun approach of jamming everything imaginable, from England and from aircraft and ships. It was a costly waste of time and resources, because, of course, the V-weapons were guided by internally preprogrammed timing and heading (V-1) or pure laws of ballistics (V-2). The scientists might just as well have been jamming already-thrown hand grenades.

The fact that both the Germans and Japanese, separately, finally resorted to copying captured three-year-old-designs of radar systems, when most elements of the copied designs were already in the hands of their own military, but kept secret, speaks to the inefficiency of the bureaucracy of their military departments. The long-lasting German one-year rule was adhered to, religiously, until the H_2S was found, in January, 1943. Radars developed before that date were necessarily rushed into the field with serious shortcomings in electronic countermeasure robustness, and, sometimes, in physical characteristics. The *Wassermann* radar, used to plot the flights of Allied planes in order to get the most out of the Bf109 and Focke-Wulf 190 interceptors (much like the Brits had done with Chain Home to win the Battle of Britain), had its antenna system built on a tall tubular metal pole. While quite rigid and strong, the pole had to rotate around a supporting, concentric inner pole in order for the antenna to track moving targets, and if the two concentric tubes got bent or dented, well, that would be the end of the rotation feature. But the real weakness was that the antenna simply had to be rotated to a particular azimuth in order to align the two tubes' hinges, so that the antenna could be lowered for repairs. The alternative, repairing the antenna elements "in the air" required the use of a crane carrying aloft a repairman in a bosun's chair, a very time-consuming proposition. Therefore, Allied fighter-bombers, like Mosquitoes and Thunderbolts, would routinely seek out these radars, and strafe them, which usually holed the tubular masts and put them out of commission for months.

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[90]For an excellent illustration of this ferret technique, see Schlesinger, Robert J., *Principles of Electronic Warfare*, pp3,4, Prentice-Hall, 1961.

Half a world away, the Japanese military were having the same sorts of problems playing catch-up in radar.[91] Recently, H. Nakajima, writing in *The Radioscientist* described[92] in a whole new light Japan's efforts to produce a military radar. He writes that the scientists were thwarted on every side by a stubborn and indecisive military, mainly the Army. He claims they had a magnetron-powered[93] 10-centimeter-wavelength radar, described as their Mark II Model 2, in use aboard ship during 1942 and 1943, the same period when their army was searching desperately for a clue as to what frequency regime was best for flak-control radar, for aircraft-detection radar, and for airborne-interceptor radar. In their search, they tried German *Würzburg*, *Freya*, and *Lichtenstein* radar designs, American SCR-270 designs, and what they could find out about the British/American ASV/ASB airborne radars.[95] All the while, if they had pressed the Mark II Model 2 radar into Army service, they would have fared much better than they did with the VHF/UHF radars they finally did employ. Interestingly, Nakajima writes that the reason Japan could not use the magnetron in their Army radars was the shortage of permanent magnet materials, such as cobalt and nickel. That excuse seems to lack credibility. (What was wrong with electromagnets? An early [1941] coastal-defense US Army radar, the SCR-296, operating at 40-cm wavelength, used electromagnets on its magnetron, simply because permanent magnets that size would be hard for workers to work with [they tend to stick to everything], and their magnetic fields would be too variable, unit-to-unit.)

Today, it seems astonishing that there was no effective technological cooperation between Japan and Germany, as there had been among the Allies.[95] If there had been Axis cooperation, *and* if it is true that Japan had a 10-cm multicavity-magnetron-powered radar design by 1939, the story of the Battle of Britain (and the second World War) would certainly have ended differently. Ambassador Joseph Kennedy and Lord Beaverbrook would have

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[91]Terrett, Dulaney, *op cit*, p129.

[92]Nakajima, S., *loc cit.*

[93]Nakajima claims that Okabe invented the basic magnetron, and, presumably, the multicavity magnetron shown in his article. Okabe, however, in a rare 1937 book written in English (and found by the American Army in a suburban Munich library in 1945) credits the invention of the multicavity magnetron (which Okabe describes as "interesting") to A. L. Samuel, of Bell Labs. See footnote 25.

[94]Over 26,000 of the ASB-5 airborne radars were produced in the war.

[95]What technological interchanges that did take place were impromptu, and were never planned from the war's outset, as were ours with Britain, Canada, and Australia. The main problem seems to have been mistrust of the true Japanese intentions and commitment by Germany's von Ribbentrop. He felt that Japan would not stay in the war if the US entered on the side of the British. Conversely, he was not anxious to declare war on the US unless he could persuade Japan to help out. Consequently, he was caught by surprise when the Japanese attacked Pearl Harbor.

been right.[96] Germany would have had no problem carrying out night bombing, right from the outset, and the RAF could probably have been eliminated with this bombing. There would have been nothing standing between an all-German Europe and America.

The crucial question is: Why did not the Germans develop magnetron-powered microwave radar? The [scarce] little book by Kinjiro Okabe referred to in these footnotes describes Okabe's state of knowledge of magnetrons as of 1937. There is ample reason to believe that Nakajima (see footnote 24) was unaware of its contents, and other contemporary journals do not refer to it (although Okabe is featured heavily in IRE Proceedings of the mid- and late-1930s.) This author has seen but two copies of this book, one[97] of which had been liberated from a suburban Munich military library[98] in 1945 by the US Army' Evans Signal Lab; thus it was available in Germany during the war, and likely before the war. Here were the basic operating principles of the magnetron and a drawing of Samuel's four-cavity anode microwave magnetron. So even if Japan did not really have an operating multicavity magnetron before 1944, the information on how one might be built was available both in Japan and in Germany, in Okabe's book. It is likely that the utter secrecy of weapons development in Germany, if it resembled, even slightly, the paranoia in wartime America, worked against the acceptance of any open literature as a genuine source of trustworthy technological information.[99]

In the war's waning months the allies did not need the kind of early-warning radar represented by Chain Home, except for use against *kamikaze* aircraft and German V-1 and V-2 missiles. Thus, the use of radars having wavelengths longer than 60-cm was on the wane, being replaced by microwave systems of 10-cm and 3-cm wavelengths. These were being used for

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[96]Kennedy had left London for America as the Battle of Britain started, convinced that Britain was finished. While in Washington, he convened a meeting with Beaverbrook and former German chancellor Heinrich Bruning to consider offering Germany a peace plan, with Bruning as chancellor over Germany at her present size (including most of Poland, Czechoslovakia, Austria, and part of the Alsace).

[97]The other copy is the one reviewed by Ross Kilgore for the *Proceedings of the IRE* (Sept 1938 issue) and was retained by him.

[98]The book is stamped: *Bücherei des Flugfunk-Forschungsinstitutes Oberpfaffenhofen e.V.*, General Wolfgang Martini's organization.

[99]The invention and patenting, in 1939, of the first frequency-hopping secure communications technique, by actress Hedy Lamarr and George Antheil had been discounted by the US Navy (even though the Navy yearned to use the method) owing to their fear that she, being an alien (Austrian), might have already compromised the technique's secrecy by divulging it to her native country's government sometime in the past.

everything from search to fire control and ground-controlled intercept. The adaptation of these radars to ground-controlled landing, for socked-in airport conditions, was most visible in the immediate-post-war Berlin blockade by the Soviets. Meanwhile, by war's end, both the Germans and Japanese had gained an appreciation for these short-wavelength radar techniques, but their industrial bases were decimated so that practical systems could not get into the hands of the users. Yet innovation in the field by the military was often brilliant. In 1941, when the US Navy outfitted Pacific submarines with the 115- MHz model SD radar which would locate distant Japanese patrol aircraft in time to permit an orderly dive for safety, Japanese ships and aircraft picked up the radar's pulses from ranges well beyond the radar's capability, correctly analyzed them, and then tracked them to their sources, causing considerable losses among the American subs. It took a crash effort by NRL to redesign the radar transmitter pulse modulator[100] so that it sent only a short string of pulses, enough to give the submarine skipper a quick look around, but not enough to let the enemy find the direction from which the pulses came.

In the main, the effort of the Germans, especially, was one in constant flux, in which new capabilities replaced previous models of a given system almost weekly. Hampered through most of the war by a strict requirement that electronic systems had to get from drawing-board to battlefield in less than one year, their more complex systems could not adapt to a changing war condition. This precluded the effective development of radar countermeasures. Only after the discovery of the British H_2S radar in the crashed Stirling bomber, in January 1943, did the *Wehrmacht* high command rescind that one-year order, and then it was too late. Coupled with the relaxation of the one-year rule was the return of the traditional German quest, in nearly all their developments, for the very best in performance. This was in stark contrast with the British maxim, sometimes attributed to Churchill: **Take third best; the best you can never have, and second-best will be got too late.**

Postscript

After the war, all countries except the Soviets cut back, tremendously, in the area of radars able to do what Chain Home did, provide early warning. The US. ringed major cities with Nike batteries, which were useless to stop nuclear bombs from destroying the cities they surrounded. All around America were 10-cm radars, not unlike the SCR-584, while all around the USSR were the originals, SCR-584s and their replicas. In Britain, no major radars were erected, except the giant BMEWS in Scotland. It stared out into space, looking for the telltale track of ballistic missiles enroute to America.

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[100]Gebhard, L.A., *op cit*, pp186,187.

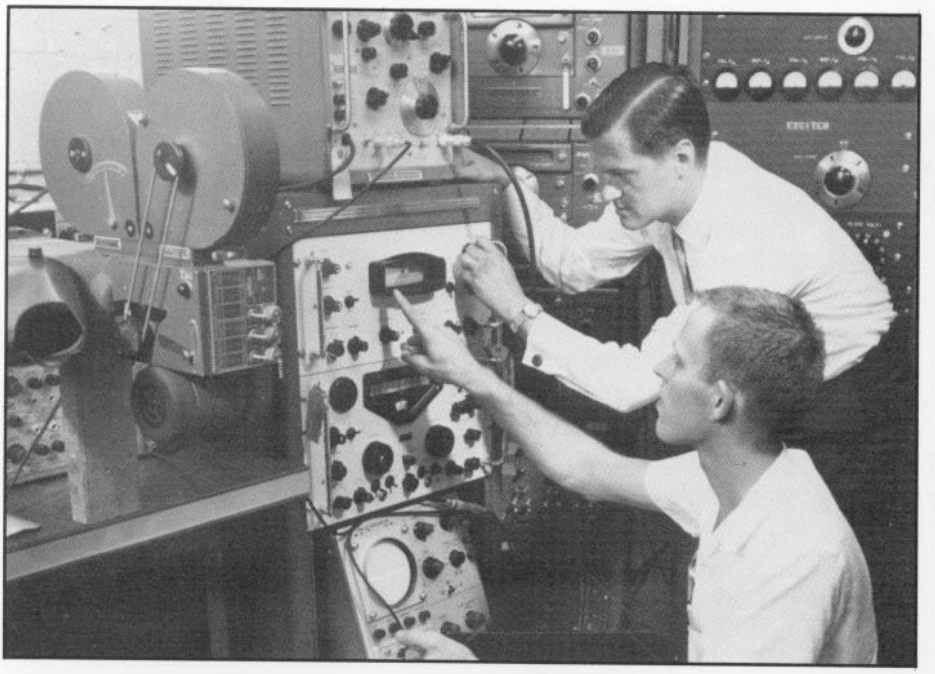

Figure 27. William J. Thaler and this author at the controls of an early frequency-agile, over-the-horizon (OTH) radar in 1957. They are searching for a clear shortwave channel, using a Racal RA-17 receiver and its panoramic adaptor. Note the superficial resemblance between Thaler, recognized as the prime mover in the development of OTH radar, and A. Gerald Touch, British developer of the ASV type of airborne radar. (US Navy Press Release Photo.)

In America, the Naval Research Laboratory, where western radar was born, put together some shortwave radio components and made up a radar very much like Chain Home, except for its detection sensitivity. It was called MUSIC, and was tested in the 1947-1954 time period. It was followed by a very capable radar, also operating at 26 MHz, called MADRE, which detected missile launchings 1000 miles away, and routinely detected aircraft over 1500 miles distant, well beyond the horizon. In this work NRL was exploiting the accident of Chain Home, in which it inadvertently detected objects deep in Europe, because of the short-wave ionospheric "skip" effect. In "skip," as all amateur radio operators know, the ionosphere refracts, or bends, the transmitted signal ray paths back down to reach the earth a thousand or more miles away from the transmitter. This was the deliberate birth of over-the-horizon (OTH) radar, if Chain Home was its accidental birth.

One of the early American experimenters in OTH radar was Dr. William J. Thaler, now a professor in the Physics Department at Georgetown University. He was supported by NRL and several other scientific organizations, including ACF Industries (later a part of ITT) and Stanford

University. The work at NRL was led by F. Malcolm Gager and James Headrick, while the ACF work was led by Bill Whelan and this author, and at Stanford Dr. O.G. "Mike" Villard and a succession of bright graduate students headed the group. In 1957, Thaler's ACF group began the fielding of some 14 OTH radars throughout the world, to carry out intelligence-gathering missions until satellites could finally be developed, and successfully launched, to carry on this work. Both the Air Force and Navy have developed operational OTH radars patterned after the early designs of Gager, Villard, and this author, and their colleagues.

These radars are, by far, the largest ever used on earth. They are able to survey millions of square miles of area surrounding the North American continent, out to distances of 1500 miles or more from our shores. They operate in the 5-30 MHz, or "shortwave" region of the spectrum, as did Chain Home. Trouble is, they don't look at all like "radars," and this was the sort of thing which first led Goering and his General Martini to discount the Chain Home system. Could it be that this oversight, along with the many other accidents and incidents related in this story were the product of some sort of divine conspiracy?

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The Antique Wireless Association Convention
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The second World War was won by both the quantity and quality of the armaments produced by the Allies, primarily America. Radar, the technology which permits "seeing" in the dark, and in fog, smoke, and cloud, was one of those armaments most directly responsible for the Allied victory. Basically, radar consists of illuminating a target with radio waves and detecting the echoes of the target. This is like shining a flashlight on some object so that the very complex reflection we call its image is returned to the observer's eyes, where it is "seen." The aim of the developers of radar was night vision, and to approach an acceptable level of radar resolution, it was necessary to develop transmitting and receiving systems operating on extremely short wavelengths. The technological breakthrough which enabled the production of powerful radar transmitters (bright flashlights) was the multicavity magnetron, a vacuum tube able to produce millions of watts of pulsed power at wavelengths of a few centimeters. By contrast, ordinary shortwave radio operates at wavelengths of tens of meters, and TV operates at wavelengths of the order of a meter.

1. The Official Cavity Magnetron Background

In late August, 1940, the *HMS Duchess of York* set sail from Liverpool to America, carrying a precious load. Aboard was a contingent of British scientists and military officers and men, all expert at the design or operation of RDF, the British initials for what we in America would eventually call **radar**. Leading the group was Sir Henry Tizard, Rector of the Imperial College of Science and Technology, and with him were three civilian experts and three officers from each of the RAF and RN. Also aboard was a small cargo containing two very precious vacuum tubes called multi-cavity magnetrons, and an airborne radar set called the ASV (for Air-to-Surface-Vessel). These particular magnetrons, serial numbers 6 and 7, had been developed in Britain by Randall, Boot, and Oliphant, of Birmingham University, while the ASV had been the brainchild of Harry Touch.

Once here in America the Tizard Mission, as the group was called, started on their tour of American and Canadian centers for the development of radar; here, that meant the Signal Corps facilities at Ft. Monmouth and the

Naval Research Lab at Anacostia. The Americans being visited knew precious little of the purpose of the Mission, but to both the British involved and the highest US Government officials, including Roosevelt, the purpose was singular, and quite clear. Some six months earlier, Winston Churchill had been briefed on the advances being made in RDF, and in the large part played by RDF in normalizing the lop-sided odds in the battle between the *Luftwaffe* and the RAF. He had concluded then that although RAF Fighter Command was whittling away at the *Luftwaffe* bomber force, causing costly attrition in German crews, the war could still easily be lost, especially if and when the *Luftwaffe* became effective in night bombing. He ordered Lord Cherwell (Lindemann), his science advisor, to see to it that the RDF breakthroughs and other weapons inventions were disclosed, in their entirety, to Canada and America, so that those two nations could carry on the war against Hitler, even if Britain fell.

The matter was spelled out to the British ambassador to the US, the Marquess of Lothian, who promptly contacted Roosevelt with the proposal:

[His Majesty's Government]... would greatly appreciate ...[it, if the Americans, upon given the full details of the British advances in RDF and other matters]... would reciprocate by discussing certain secret information of a technical nature which the British are anxious to have urgently.

Lord Lothian was very anxious about one point: he did not want it to appear that there was any sort of bargain here. His country was about to tell all their latest military technology secrets to a potential ally, no matter what; as a separate matter, then, could that ally possibly help Britain in their struggle to survive, by sharing some of the ally's secret information? He was fearful that at the technical level the participants in the exchange would behave as though it was strictly *quid pro quo*. This might stifle a free exchange, for if one side felt they were not getting much from the other, they would hold back; on the other hand, if one side felt the other side was overwhelmingly superior, technologically, an inferiority complex might set in which would also damage the depth of the exchange. Both of these effects, in fact, were in evidence during the ensuing few weeks.

The Mission's first official stop was in Canada, where their primary inventions had already been disclosed, but only in Government circles, and not to industry. By the second of September, though, Tizard was in General Mauborgne's[1] office, briefing a select group of officers and scientists on the

[1]Chief Signal Officer of the US Army Signal Corps.

latest in British RDF or radar. The British reviewed how their RDF had started, in the Chain Home system (operating at 12 and 24 MHz), and had progressed upward in frequency with each major development, culminating in a possibility of an airborne system for night fighters, the H_2S RDF, operating at 3000 MHz. The Signal Corps scientists, who had also been through the low frequency developments, and who were prepared to release to the Brits some tidbits of information on their SCR 270, which operated at 110 MHz, listened intently until their guests began talking about the 3000-MHz aircraft intercept (AI) system they were then designing, using the new magnetron. From this point onward, the Army people felt that their work was considered inferior, and this was emphasized by the presence of a US Navy officer at the briefing, who chimed in with comments about a Navy 3000-MHz radar effort underway, one which also used a magnetron. Del Hershberger, chief radar scientist with the Signal Corps, saw that his opportunity to brag about the early (1933) work his group had done in radar detection of trucks and planes using a magnetron-powered 9-centimeter wavelength radar set, had vanished, and that now it would sound like a "Me, too!" The Signal Corps hosts became suddenly silent, and the meeting grew awkward, everyone wishing it could end. Lord Lothian's worst fears had come to pass.

On the 12th of September four members[2] of Tizard's group visited the Naval Research Laboratory, where A. Hoyt Taylor, Leo Young, and Admiral Bowen took part in the discussions, and presented briefings on their own accomplishments in RDF or radar. They had been assured that there would be no secrets held back, and if the meeting seemed to go quite smoothly, it was partly because Tizard and E.G. Bowen had run down to NRL on August 30th for a preliminary discussion even before meeting with the Canadians. At this earlier meeting Tizard had none of his prize inventions with him, but there had been much discussion of radar system design.

By the 17th of September the meetings got around to the magnetron, and Tizard mentioned, rather offhandedly, the output power level of 10 kilowatts easily reached using this device. The NRL staff quickly questioned such claims, and were told that the rating referred to pulsed r-f power being extracted from the 3000-MHz magnetron Tizard showed them. The average power rating was down around 10-20 watts. NRL's own experience with wavelengths that short, using a magnetron oscillator as the transmitter, was that only a few hundred watts pulse power was obtainable. It was then that Tizard showed a cut-away model of their magnetron, with its six cavities surrounding a central cathode assembly. Taylor studied the model carefully,

[2]Tizard, E.G. Bowen, J.D. Cockroft, and a Royal Navy officer.

and said that it didn't resemble theirs, which looked more like a standard glass transmitting tube, but with internal resonant circuit elements. Cockcroft explained that the multiple cavities were the secret to high power and high efficiency. What wasn't fully understood, even by Cockcroft, was that the replication of the cavities around the cathode allowed the tube to oscillate in a mode entirely different from that of the earlier NRL magnetron.

The magnetron was immediately taken to Bell Laboratories' Radio Lab in Whippany, NJ, for examination and testing. There, Bell had a Navy shipboard fire control radar under development, operating at 700 MHz (wavelength of 43 centimeters), and the engineers there were struggling to get 2 kilowatts pulse power from its transmitter, powered by two special triode tubes. The British magnetron was X-rayed and was found to have eight cylindrical cavities, contrasted with the drawings, which showed six, as did the cut-away model shown to NRL. Bell's tests of the unit showed it to develop over ten kilowatts of power in 1-microsecond pulses, recurring at 1000 pulses per second. The Americans were in utter awe. Robert Page shook his head, noting, "This is nothing at all like the early magnetrons. I think this will make all the difference in the world, and now our polar display will make sense!" He was referring to NRL's PPI radar display, which made map-like presentations of what the radar "saw."

2. The Early Magnetrons

In early 1915, Albert W. Hull, working at GE's Research Laboratory in Schenectady, concentrated his attention on two electron tube phenomena, aiming at avoiding interference with the patents of deForest or Fleming. These two phenomena were negative resistance and magnetic electron-flow modulation. His negative resistance experiments led to the development of the dynatron, and the magnetic modulation of tube current was embodied in the magnetron.

Hull's background was in classical Greek, English, and physics, and he had been fascinated with the classic physics experiment attributed to Thomson in which electrons are just prevented from striking a positively-charged anode by a carefully adjusted magnetic field. In this experiment, the object is to calculate, from the magnetic field strength and the anode voltage, the ratio e/m, or the charge per unit mass of the electron. At GE, Hull reproduced the experiment to study the control of electrons flowing from cathode to anode exerted by an applied magnetic field. Using flat planar anodes and mesh cathodes, he was disappointed in his inability to detect the sharp anode current cutoff expected at the critical level of magnetic field. Reasoning that the main problem was due to edge effects on the anode, which

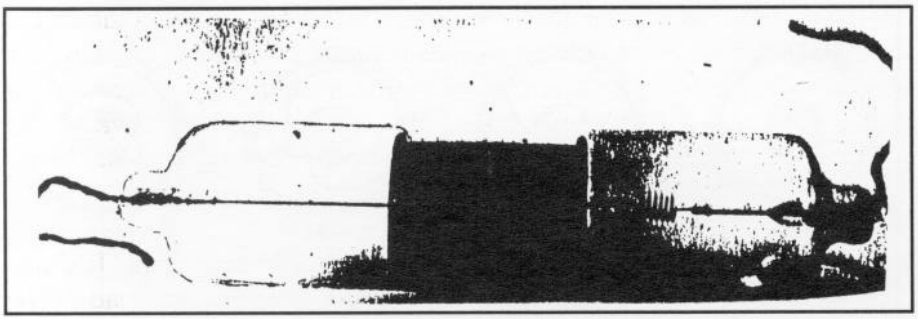

Figure 1. A. W. Hull's original single-anode magnetron, with coil removed.

distorted the electric field, he bent the anode into a cylinder surrounding an axial cathode filament, thus avoiding anode edges altogether.[3]

His magnetron tube, shown in figure 1, thus had a central filamentary cathode and surrounding cylindrical anode, or plate, with a magnetic field, also axial, to deflect the electron motion, thus offering the possibility of electron flow control without the use of an interposing grid as in deForest's triode audion. His timing was not good, as the war effort soon diverted all his attention to developing electron tubes needed by the Signal Corps and Navy, regardless of patents. By 1919, he was back at the research[4] into magnetrons, though.

Hull puttered around with this basic cylindrical form of magnetron in the 1919-1924 period, obtaining four patents on the device, even though the post-war period saw a settlement of the audion legal problems and the elimination of the original need for the magnetron. He left most of the further work on the tube to his subordinates, Frank Elder and E. D. McArthur.

The Hull magnetron was a cylindrical diode, surrounded by a magnetizing coil coaxial with the anode and filament, which could be energized to produce a magnetic field along the axis of the anode and filament. Simple theory would hold that the electrons emitted by the hot filament should be accelerated toward the anode, owing to its positive voltage, and that, in the absence of a magnetic field, the electron paths would be straight to the anode. With an axial magnetic field present, though, such as would occur if the coil were energized with d-c, the electron paths should become curved into spirals toward the anode. At more intense magnetic field strengths, though, the

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[3]Hull, A.W., in interview by Nat'l. Acad. Sci. biographers C.G. Suits and J.M. Lafferty, Columbia Univ. Press, 1970.

[4]Hull, A.W., *Physical Review*, Vol 18, p. 31 (1921), and
Hull, A.W., *Physical Review*, Vol. 23, p. 112 (1924).

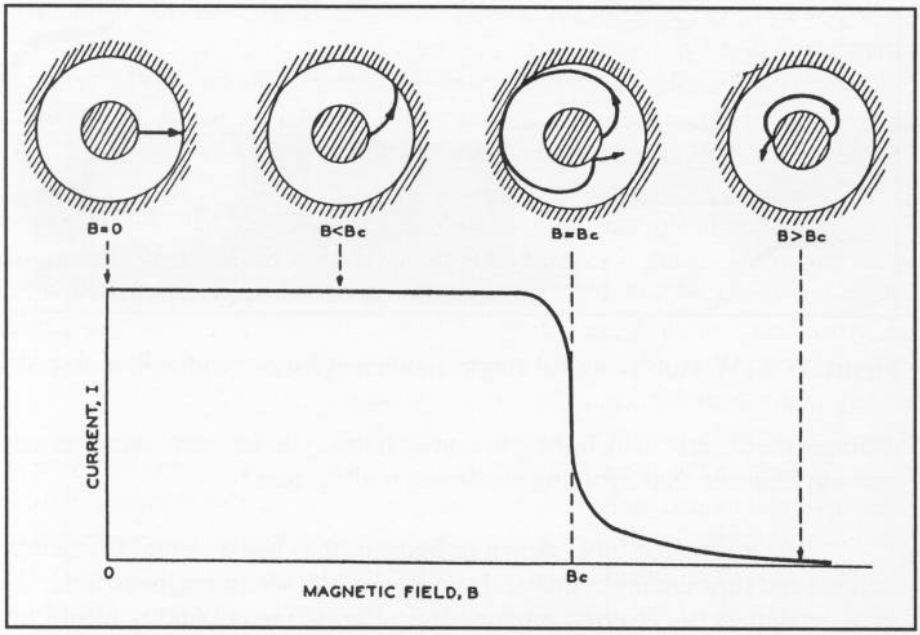

Figure 2. Typical magnetron anode current characteristics.

spirals would become tighter, until, at some critical field strength, the electrons would fail to reach the anode, and would circulate around the cathode. With a good hard vacuum in the tube Hull and McArthur were sure they found the sharp anode current cutoff with application of the critical magnetic field strength, and thus reach the high-gain part of the tube's operating characteristics. (See figure 2.)

Elder successfully used Hull's cylindrical-anode magnetrons as straightforward amplifiers and oscillators in 1924. When used as an amplifier, the input signal was impressed on the coil and the changes in anode current, caused by the magnetic deflection of the electrons (into spirals rather than the straight stream to the anode), but the device was far from stable. So he resorted to a feedback connection in which the anode current was fed back to energize the coil, and in which there was a d-c biasing coil as well. When the d-c bias coil was set to the verge of anode current cut-off, the system oscillated, and the oscillation frequency could be set by tuning the coil. Hull and Elder realized there were losses being introduced by the anode acting as a short-circuited secondary turn of wire in the transformer formed by it and the coil, so Elder had a technician split the anode into two sections. Elder continued with the feedback oscillator circuit, though, and was able to get several kilowatts of r-f power from a magnetron only four inches in diameter and a foot long. By 1925, Elder[5] had built a magnetron oscillator making 15 kilowatts

[5]Elder, F.R., Proc. *I.R.E.* Vol. 13, pp. 159ff (1925).

c-w power, but at a frequency of only 20 kHz. His aim was to introduce the magnetron to the power transmission and VLF communications groups of the electrical engineering fraternity. At the same time, Elder and Hull worked out a receiver-sized three-stage magnetron amplifier able to pick up, in Schenectady, radio signals from Germany.

In Czechoslovakia, though, in 1924 August Zacek began working with the magnetron, using a single-anode configuration based on Hull's original designs. Zacek reported, in the German journal *Hochfrequenztechnik und Elektroakustik* in 1928[6], detecting 1000-MHz signal coming from the device. These oscillations were at a frequency far above any he could receive with instruments available, except for a lecher line and lamp bulb.

Then in the same year (1924) in Germany Erich Habann discovered a negative-resistance characteristic in a magnetron having a split anode.[7] Further, he noted that the frequency at which such a magnetron would oscillate was a function only of the tuned circuit he placed in the anodes' circuits. Thus, he may have produced r-f oscillations at wavelengths similar to those obtained by Zacek, but such was not reported. Interestingly, Zacek didn't understand from whence the oscillations came, and Habann, expecting oscillations, did not attempt to find an upper frequency limit of these oscillations. The work of these two Europeans was unknown to Hull's group until 1928, when Zacek's paper was published in the German journal.

Meanwhile, in Japan, Professor[8] Hidetsugu Yagi, better known for his invention of the Yagi antenna, had the idea of a magnetron brought to him from

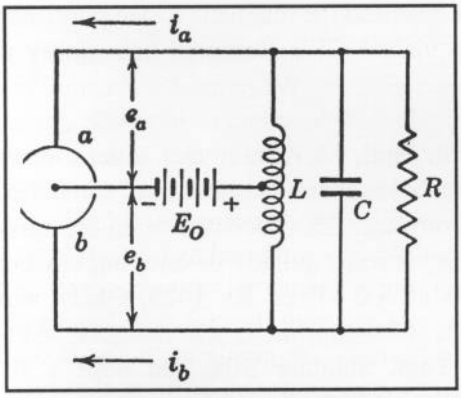

Figure 3. Split-anode magnetron with tuned anode circuit.

[6]Zacek's article was a reprint (translated into German) in the German journal. He had published the same material in Prague in *Casopsis pro pestorant mathematiky a fysiky*, Vol. 53, pp. 378ff, (1924).

[7]Habann, E., *Hochfrequenztechnik und Elektroakustik*, Vol. 24, pp. 115ff, (1924).

[8]At Tohoku Imperial University in Sendai, Japan.

America, by virtue of a description of Hull's device by a Japanese naval officer who had visited GE in Schenectady. Yagi had a bright doctoral candidate student working in the lab for him, Kinjiro Okabe. Okabe was teaching undergraduate physics in 1927, and was trying to duplicate Thomson's experimental measurement of *e/m* of the electron, using crossed electric and magnetic fields. Thus, Okabe built a magnetron according to the description Yagi gave him, and tested it for its sharp anode current cutoff as the critical magnetic field strength was approached. Embarassingly, the sharp cutoff was anything but sharp, and the anode current actually jumped back up as the magnetic field was increased beyond the critical level, confounding Okabe and his students. Based on Hull's description of achieving the theoretical Thomson behavior of the magnetron, and of Hull's repeated failure to observe the Thomson effect (sharp current cutoff at critical magnetic field strength) until he had hardened the tube vacuum, Yagi advised Okabe to improve the vacuum and keep trying, guessing that the current anomaly was caused by gas ions. The "bump" in the anode current curve persisted, though, and was quite large when he used a split-anode form of the tube.

Okabe suspected that the tube was in oscillation, since he had seen similar anomalies in ordinary triode tube behaviors when the circuit in which the tube was connected began to oscillate. Unable to detect the oscillations with a radio, he set up lecher lines and found a strong output from the tube in the 500-MHz region, which was tunable in frequency by varying the lengths of the magnetron anode lead-in wires. He applied for a Japanese patent on the circuit immediately (1927), and applied in America the next year, assigning the patent to GE. In 1928, Professor Yagi came to America and addressed several technical groups on his research in antennas and the magnetron. He published a paper in the *IRE Proceedings*[9], and visited GE's Research Laboratory at Schenectady.

At Schenectady, Yagi met with Hull, McArthur, and several other engineers, and his description of Okabe's magnetron oscillations stimulated fresh new thinking at GE. From then onward, GE concentrated on the split-anode and quartered-anode types of magnetrons, quickly developing devices able to produce several hundred watts at 400-MHz. By 1929, Okabe was publishing papers describing oscillations at 5.6-centimeter wavelengths, and in 1930, another student mentored by Yagi, Shintare Uda, had built a 30-kilometer-long communications link using magnetrons and Yagi antennas on a frequency of 1000 MHz (30-cm wavelength). Both Okabe and Hull's group came to realize that only in the split-anode type could they get oscillations whose frequency was controlled by the tuning of the anode circuit, as in figure

[9]Yagi, H., *Proc. I.R.E.*, Vol. 16, pp. 715ff, (1928).

3. In the single-anode type, the oscillations were at a frequency set by the anode voltage and the magnetic field strength, and not directly influenced by the tuning of the anode load circuit. In 1930, Okabe published a paper differentiating between the two types of oscillations, and the desirability of achieving the "Type B", or split-anode tunable oscillations.

3. The Drive to Shorter Wavelengths

In Europe, more groups of engineers and scientists began searching for ways of transmitting and receiving signals of extremely short wavelengths. What had triggered this activity was the success being realized by the GE group in America, producing air-cooled magnetrons capable of several watts output and water cooled units able to make several hundred watts. In addition, Yagi had suggested in his papers that these new ultra-short wave signals could be directed into narrow beams, using Yagi-Uda antenna systems, to allow relative secrecy in communications. The higher frequencies would also allow the use of large signal bandwidths, which implied the transmission of many communications channels at once.

Most of the research in magnetrons in Europe took place in the early 1930s by IT&T's labs and *Compagnie Générale de Télégraphie sans Fil*(CGT), both in France, using split-anode magnetrons based on Okabe or GE designs. M. Ponte, of CGT, reported in 1934 on microwave communications links powered by 40-watt magnetrons operating at frequencies from 600 to 4200 MHz (wavelengths from 7 cm to 500 cm). In 1935, the French outfitted the steamer *Normandie* with an iceberg-detecting pulsed radar device using a magnetron operating at 1800 MHz (wavelength of 16 cm). In this period, the two major contributions of the French were (1), the incorporation of large-diameter indirectly-heated oxide cathodes which greatly increased the electron density in the tube and raised the peak power available, and (2), the discovery that increasing the number of anode segments enabled large increases in the frequencies of the signals produced. These two contributions were to have a large influence on the British magnetron eventually brought to America by the Tizard Mission.

At GE, several models of split-anode magnetrons were developed by McArthur and Chester Rice. The largest of these was water cooled, and produced 2.5 kW at a frequency of 75 MHz, while Rice's was made for higher frequency operation, and was used by him in communications tests over a six-mile range at a frequency of about 7500 MHz. By placing a receiver and its antenna alongside the transmitter and its antenna, both aimed at nearby objects, he was able to detect the echoes of automobiles and aircraft moving in the beams, and he suggested the use of the method as an all-weather true altimeter for aircraft. Rice commented that the microwave power produced by

his transmitter was sufficient to cause uncomfortable burns on his fingers when he touched the transmitter antenna.

In America, aside from the magnetron research going on at GE, Westinghouse, and some universities, a completely different area of research was being pressed to its logical conclusion: finding the upper frequency limits of ordinary (and not so ordinary) triode vacuum tubes. Here, GE's Schenectady labs led the way in one of the efforts, while RCA and Bell Labs worked on two other efforts. E. McArthur at GE Labs conceived the idea of triode tubes having extremely low inductance in the lead-in conductors feeding the cathode, grid, and anode. He achieved this result by means of the disk-seal, a glass-to-metal bonding developed by Hull himself, which allowed the use of metal disks extending through the glass bulb to connect the electrodes. The disk type leads were practical only if the tuned circuits connected to the tube were similarly arranged, and this was made possible as a result of the continuing analyses of metal cavities as resonating circuits by W.W. Hansen, from 1935 to 1938[10]. By using cylindrical cavities as tuned circuits, in which the cylinder ends were, in fact, the vacuum tube's disk seals, McArthur was able to obtain oscillations at several watts power level at frequencies as high as 1200 MHz. GE's 2C40 and 2C43 "lighthouse" tubes, developed in 1940, were the result of McArthur's research in this area. Hansen's tuned cavities were also to play a critical role in the further development of the radar magnetron and other microwave devices.

Meanwhile, in 1931 Langmuir[11] published an analysis of triode tubes and their natural upper frequency limits, based on the inherent relationships between tube size and inter-electrode capacitance, lead-in inductance, and electron transit time. His treatment pointed toward very small tubes as having the most promise for getting to frequencies as high as 3000 MHz. B. J. Thompson and G. M. Rose[12], of RCA, immediately pursued this field of effort, trying to implement the same sort of "microray" communications links as the French were rumored to be working on. These small tubes had short leads arranged radially through the side of the bulb, and were able to operate as oscillators at 1000 MHz and above. These were the well-known acorn tubes of the period from 1935 onward. Maximum power levels of these tubes was in the one-watt region, which was nice for receivers but not for radar transmitters.

At Bell Labs, tube research aimed at getting tubes to produce high power at frequencies as high as 3000 MHz was in the hands of Arthur Samuel.

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[10]Hansen, W.W., *Physical Review*, Vol. 47, pp. 129ff (1935), and *J. Applied Physics*, Vol. 9, pp. 654ff (1938).

[11]Langmuir, I., et al, *Rev. Modern Phys.*, Vol. 3 No. 2, p. 352 (1931).

[12]Thompson, B.J. and G.M. Rose, Jr., *Proc. I.R.E.*, Vol. 21, pp. 1707ff, (1933).

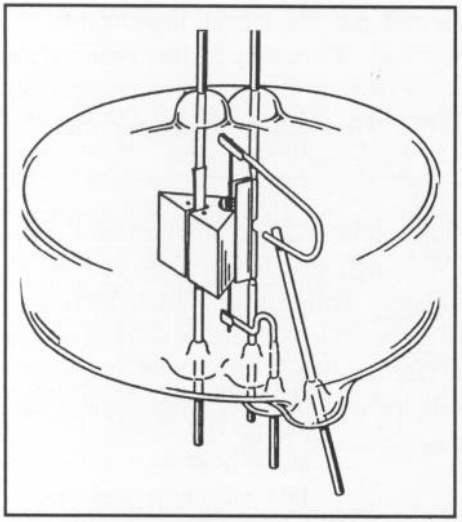

Figure 4. Arthur Samuel's power triode for UHF Lecher lines.

He approached the problem of Langmuir's size reduction in a clever way, reasoning that very small tube structures made for ultra-high frequency operation, but at miniscule power levels. Instead of making the tube smaller, he made the tube's electrodes an integral part of a lecher-line tuning system[13]. He ran the lecher lines right into the tube envelope, and in some designs, right through the tube. From these internal lines he mounted anode, grid, and filament, all of robust thickness, but with very low interelectrode capacitances. Figure 4 shows one such tube. Note the anode, triangular-prism-shaped to offer low edge capacitance, but massive enough to dissipate several watts of power. This family of tubes became the well-known "doorknob" tubes, Western Electric's contribution to radar electronic countermeasures and identification of friend or foe (IFF), important adjuncts to radar.

4. Internal Tuned Circuits - The Next Step

Samuel's work toward bringing part of the tuning lecher lines inside the envelope of a doorknob triode was extended to magnetrons, as well. Two independent efforts were underway in the mid-1930s to further reduce the size of the tuned circuits in split-anode magnetrons, and thereby achieve oscillations at still higher frequencies. Claud Cleeton and Neil Williams[14] at the University of Michigan needed a microwave source of power for spectroscopy studies, and bought a Westinghouse split-anode magnetron designed by Kilgore. It was connected to very short lecher-lines, but failed to reach the frequencies needed, around 3000 to 9000 MHz. They scaled the

[13]Samuel, A.L. and N.E. Sowers, *Proc. I.R.E.*, Vol. 24, pp. 1464ff, (1936), and Fay, C.E. and A.L. Samuel, *Proc. I.R.E.*, Vol. 23, pp. 199ff (1935).
[14]Cleeton, C. and N. Williams, *Phys. Review*, Vol. 44, pp. 421ff, (1933).

Westinghouse magnetron down in size and put the lecher lines inside the magnetron envelope, succeeding in their effort. Then they further reduced the lecher line sizes, and got oscillations at 45,000 MHz. Later, Cleeton would join the Naval Research Laboratory at Anacostia, VA where he did important radar research.

G.R. Kilgore, originally working exclusively on magnetrons[15] and ultra-short wavelength techniques with Westinghouse, but by 1936 with RCA, also used split-anode magnetrons, and clearly demonstrated the dynatron, or negative resistance mode of oscillation of these devices. He, too, worked out the problems of putting the tuned circuit (lecher lines) inside the magnetron envelope[16]. Unlike Cleeton, though, Kilgore was after very high power, and built some water-cooled internal-line magnetrons in 1936.

Finally, A.L. Samuel, of Bell Labs, began working on magnetrons, supplementing his efforts with the doorknob tubes. In 1937, he was granted a patent on a magnetron design in which the anode was quartered into four segments. Each segment was separated from its neighbors by tuned cavities, based on the 1935 Hansen designs. When the *Bell System Technical Journal* special issue on the Magnetron was published in 1946, Samuel was asked if his patented cavity-type magnetron played any part in the Labs' contribution to the development. He answered that it enabled Bell Labs scientists immediately to understand the British magnetron brought by Tizard, and to reproduce it so quickly. Bell technicians had apparently built a model of Samuel's four-cavity magnetron to satisfy his patent claims, but his unit had no means for getting rid of anode heat, and could therefore operate only at low power levels. Unlike GE's lab, Bell's Western Electric tube lab did not have the technology for large metal-to-glass seals. Their rendition of Samuel's multicavity magnetron was very much like the sketch in his patent application, shown in figure 5.

The failure of Bell Labs engineers to exploit Samuel's invention, and thereby clearly scoop the rest of the technical world in producing the ultra-short wavelength breakthrough needed for radar was their lack of understanding of how it worked. There is no doubt that Samuel's four-cavity magnetron could have oscillated at sufficiently high frequencies, but no one understood how.

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[15]At Westinghouse, magnetrons were referred to as "magnetostatic oscillators" in an attempt to be as unlike GE as possible, according to Ross Kilgore.

[16]Kilgore, G.R., "Magnetron Oscillators for the Generation of Frequencies between 300 and 600 Megacycles," *Proc. IRE*, 24, 1140, 1936.

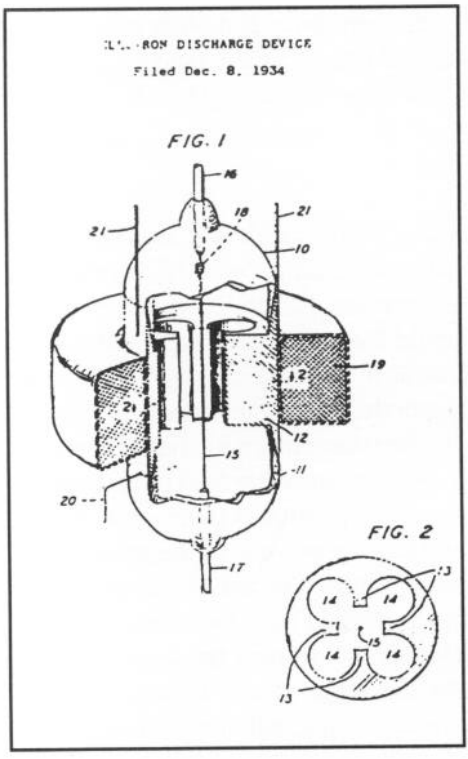

Figure 5. A. Samuel's four-cavity magnetron, from his patent.

5. Magnetron Theories

During the seventeen years from Hull's invention of the basic magnetron through 1938, many investigators looked into the magnetron to assess its value as a generator of signals for "microray" (UHF) communications systems, both for transmitting and for local oscillators in superhet receiving. A number of these researchers spent effort trying to determine exactly how the magnetron worked, since it didn't quite behave like the basic theory would dictate. For one thing, several plausible theories of operation grew out of the magnetron research of the late 1920s and early 1930s. It soon became apparent that there were several different kinds of magnetrons.

-The Feedback Circuit

The straightforward feedback circuit in which the magnetron is the active element was what GE's Frank Elder used in his exploration of the magnetron. For his circuit, the magnetron could have a single, split, quartered, or any arbitrary type of anode, since the frequency of oscillation was set by the tuning of the magnetron's external magnetic field. This was a dead-end phase of research, and, although the device could be made quite powerful, it couldn't achieve wavelengths short enough to be useful in radar.

In fact, it had all the problems of triodes, and then some. But other researchers were getting ultra-short-wave oscillations, and their circuits could be tuned by adjusting the tuning of the anode circuit, not the magnetic field coil.

-The Cyclotron Mode

Kinjiro Okabe was one of the three (with Zacek and Habann) who discovered these ultra-short-wavelength oscillations, and he eventually identified two different modes of magnetron oscillation.[17] Hull's original single-anode model could oscillate, as could the split-anode type, strictly by virtue of the precession of the electron cloud in the tube. In such a mode of oscillation, the electrons would leave the cathode, start for the anode, but would be swept into circles (actually cycloids) by the strong magnetic field. Many of the electrons would therefore return to the cathode, since it would be in the way. This explained why the cathodes in these early magnetrons often overheated or exhibited bright spots. This circular orbital motion was one of the modes Hull thought he had discovered, a mode not well controlled by anode circuit tuning. Another scenario, using the same basic theory, would have the electrons spiral away from the cathode, moving in cycloid loops toward the anode, but at sufficiently high magnetic field strengths the loops would tighten, and the electrons would likely collide with other electrons and with the filament again.

In 1934, F. T. McNamara, working at Yale, attempted to determine which electron motion characteristic was more important in the magnetron, so he proposed putting a screen or grid, also cylindrical, between the filament and anode. If the electrons were moving in circles, concentric with the cathode, they wouldn't intersect the grid very much, and any such captures by the grid wouldn't be affected by the circles being large (low magnetic field) or small (high magnetic field). He used a UX-227 tube as the magnetron, and found that when he increased the magnetic field to a strength that cut off the anode (plate) current, the grid current, which had been quite low, suddenly shot up, indicating that the electrons were running in cycloids, looping outward.

-The Dynatron Mode

The original inventor, Albert Hull, was quite active in the post-World War I period in the development of *dynatrons*[18] (negative resistance devices).

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[17]Okabe, Kinjiro, *Magnetron Oscillations of Ultra-Short Wavelengths*, pp. 4-27, Shokendo Publishers, Osaka, Japan, 1937.

[18]Hull's classical Greek higher education served to perfect the GE "greco-Schenectady" nomenclature applied to many GE products, a practice originated by Langmuir, and criticized by deForest.

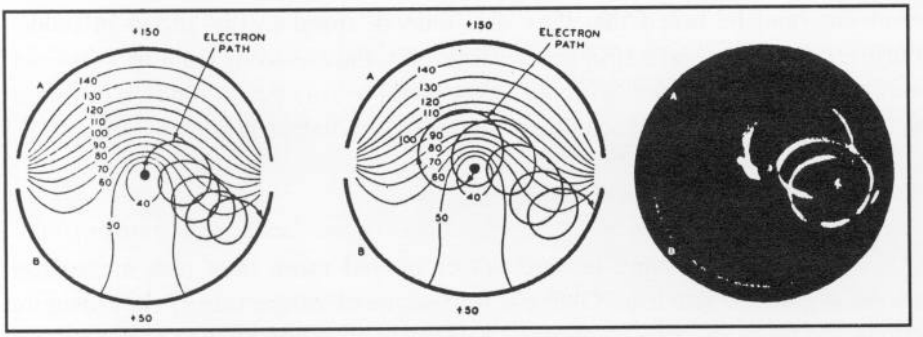

Figure 6. Kilgore's predicted and measured electron paths in a split-anode magnetron operating in the dynatron mode.

Most dynatrons relied on the generation of secondary-emission electrons in electron tubes. The phenomenon of emission of secondary electrons occurs when an electrode in the tube is struck by energetic electrons, say, from the cathode. The old UX-224 tube, our first really successful tetrode, was famous for secondary emission of electrons from the plate any time the screen grid was allowed to be connected to a positive voltage that was too high. The screen accelerated the cathode's electron stream to excessive velocities, so that when the electrons hit the plate, they dislodged a shower of secondary electrons. With the highly-positively-charged screen grid so close at hand, these secondary electrons would be collected by the screen grid. The result was a reduction in the net number of electrons delivered to the plate. Thus, if the plate were made less positive, the plate current would increase, not decrease as in a normal tube, thereby presenting negative resistance to the plate load. In this condition it could make a tuned circuit oscillate simply by being connected to the tuned circuit.

Hull's invention of the dynatron was instrumental in GE's predisposition to assign the dynatron phenomenon to the behavior of split-anode magnetrons, as soon as Yagi suggested their use as ultra-short-wave oscillators. Okabe tended to agree with this GE prejudice, at least for some modes of split-anode magnetron operations.[19,20]

Another of the magnetron experimenters, G. R. Kilgore[21], took a split-anode magnetron and reduced the vacuum purity a tad by introducing a very small amount of argon gas. Now he could see the luminescent trail of the

[19]Okabe, K. *Proc. I.R.E.,* Vol. 20, pp 1593ff, (1933).
[20]Okabe, K., *Proc. I.R.E.,* Vol. 18, pp 1748ff, (1930).
[21]Kilgore, G.R., "Magnetron Oscillators for the Generation of Frequencies between 300 and 600 Megacycles," *Proc. I.R.E.,* **24**, 1140, 1936.

electrons, and he noted that they did, indeed, spiral to the anode in loops. Further, when he used a split anode (figure 3), the electrons went to a favored half of the anode, the one with the lower positive voltage. As shown in figure 6, this graphically confirmed the existence of a dynatron mode of oscillation.

-The Spoked-wheel Mode

When these same researchers employed more than two magnetron anode segments, (such as Okabe's four-segment magnetron[22]) they usually connected them in pairs, sometimes with adjacent segments tied together, and sometimes with opposite segments tied together. They explained the oscillations as deriving either from the cyclotron mode or dynatron mode.

On the other hand, in Europe, a new theory was emerging, first from K. Posthumus, working at Philips at Eindhoven, who published his ideas in *Nature*[23] magazine in 1934. He found a natural upper frequency limit to split-anode magnetrons, despite securing tuned circuits (usually lecher lines) which should have operated well above this cutoff frequency. This was nothing new. Okabe and Kilgore had also found this problem, solvable only by making the magnetron smaller. Where Posthumus found a better solution was in subdividing the anode, and connecting segments together through separate tuned circuits, all tuned to the same frequency, of course. He found that a four-segment anode allowed frequencies twice as high as split-anodes, and eight segments allowed frequencies four times as high.

His article attracted the attention of E.C.S.Megaw, at GEC in Wembley, England. Megaw had already published[24] a good explanation of the cathode overheating problem in magnetrons (collision of circulating electrons with the cathode), and in the experimental work which supported this explanation, he also proved again the dynatron theory for multi-segment anode magnetrons. He wrote a rebuttal to Posthumus' paper, which also appeared in *Nature*. Posthumus replied, again in *Nature*[25], casting doubt on the dynatron theory, and introducing a new theory, that of a rotating field.

Before Megaw could recheck his own results, Posthumus published a full explanation of his rotating-field or motor theory in *Wireless Engineer*[26], in 1935. Megaw became convinced. They published a joint article in *Nature*[27],

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[22]Okabe, K. *Megnetron Oscillations of Ultra-Short Wavelengths, loc cit.*
[23]August 4 issue.
[24]Megaw, E.C.S., *Wireless Engineer,* Vol. 10, p. 197, (1933).
[25]November 3, 1934 issue.
[26]Posthumus, K., *Wireless Engineer,* Vol. 12, p. 126, (1935).
[27]June 1, 1935 issue.

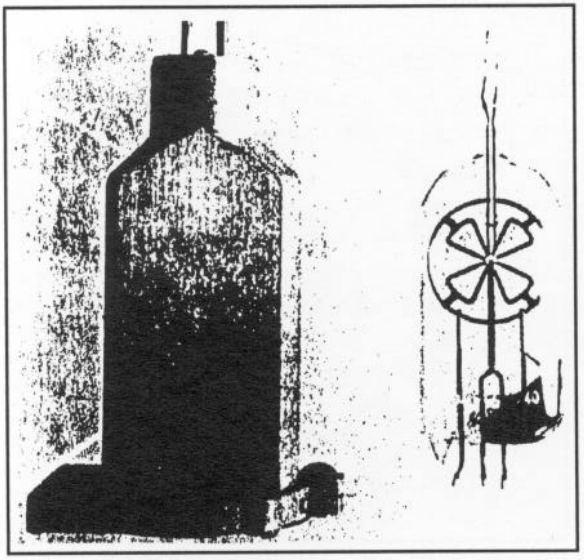

Figure 7. A four-anode magnetron by Oakbe (Japan), used in receiver local oscillator service at 3000 MHz (10 cm.).

reinforcing the rotating field concept. This theory explained perfectly the multiple modes of oscillation possible in multisegment magnetrons, with the unfortunate prediction that some of these modes yield frequencies quite close together. Okabe tested this new theory by making a small, internal-tuned-circuit four anode segment magnetron able to produce oscillations at 3000 MHz (wavelength of 10 cm.), shown in figure 7. The German engineers at Telefunken also tried out some of these circuits, leading to a sensation article in *Electronics* magazine in 1935 which described a German "mystery-ray" aircraft detection system which could see through fog and night. The Germans used only a split-anode magnetron, though.

The rotating field theory says that the initial precession of electrons around the cathode starts oscillations in each of the inter-segment tuned circuits. These oscillations cause the segments to exert a speeding, then retarding effect on the electrons, forcing them into somewhat crooked spokes from cathode to anode segments, as in figure 8. The spokes then rotate, connecting a given spoke to each segment in turn. The spoke rotation rate is a function of the cathode-to-anode distance, the magnetic field strength, and the anode voltage, and once these and the number of segments are fixed, the upper frequency limit is also fixed, just as Posthumus claimed.

6. Putting it All Together

The person who **nearly** put all the necessary pieces of the high-powered, multicavity, microwave magnetron together was Okabe. He wrote a little book[28] in 1937 in which he summarized his knowledge of the theory of

[28]Oakbe, Kinjiro, *op cit.*

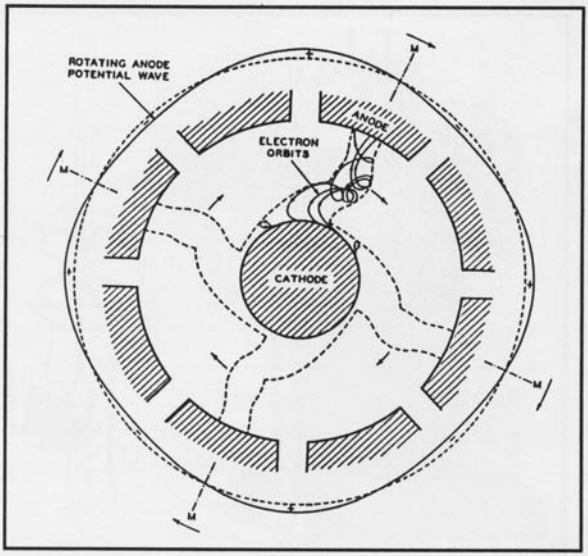

Figure 8. Spoked-wheel mode of electron flow in multicavity magnetron.

operation of the magnetron, but gave insufficient attention to the rotating field ideas of Posthumus. He did, however, recognize the use of more than two anode segments, and he described, and illustrated several "new" ideas in magnetrons, including Arthur Samuel's just-issued patent of a four-cavity (internal-tuned-circuit) magnetron. This is the magnetron which never amounted to much, probably because its anode was inside a glass envelope and hard to cool. Okabe's book (written in English, but published in Japan) was reviewed by Kilgore in the September, 1938 issue of the *Proceedings of the I.R.E.* It is a very hard book to find, my copy having been liberated by the US Army Signal Corps from the library of Luftwaffe General Wolfgang Martini's *Flugfunk Forschungsinstitut* (Aircraft Signals Research Institute) in 1945. Ross Kilgore still has the copy he reviewed in 1938.

There is evidence that Okabe soon grasped the full significance of several pieces of research to which he had been exposed. Kilgore and Linder had put the lecher lines inside the envelope, making the anode segments integral parts of the tuned circuits. Then Samuel's patent revealed a four-segment magnetron with cylindrical tuning cavities between segments. Finally, Posthumus and Megaw explained the spoked-wheel mode of electron flow, which allowed the use of massive copper anodes with the cavities and electron drift space machined into it. Quite recently, Shigeru Nakajima wrote in URSI's *The Radioscientist*[29] that Okabe had been responsible for the development of Japan's first multi-cavity magnetron, their model M3, built in 1939 by Nakajima's Japan Radio Co. This magnetron may have preceded that by Oliphant's group at Birmingham University, or it may have come later.

[29]Nakajima, S., *The Radioscientist*, Vol. 3, No. 2, pp 33ff, URSI, (1991).

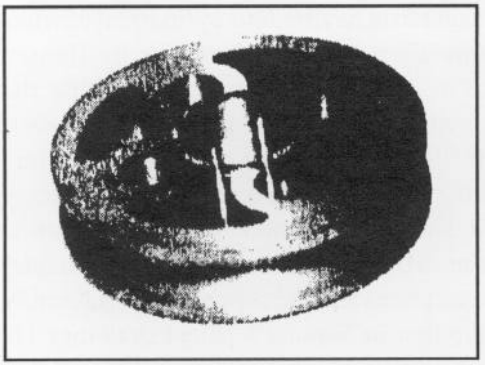

Figure 9. Japanese magnetron anode claimed by Nakajima to date to 1939.

The explanation by Nakajima that the Japanese military didn't appreciate the value of microwave radar in warfare until after 1943, when it was too late, seems fantastic. The M3 anode, pictured in Nakajima's article, and shown in figure 9, is remarkably like Samuel's four-segment unit, except for the presence of stabilizing slots, the theory of which had not yet emerged, and wouldn't until well after the war.

The scene shifts, now, to England. In 1939, Mark Oliphant, an Australian working at Birmingham University on radar, was desperately searching for devices able to produce ultra-short wavelength energy at power levels of tens of kilowatts, pulsed. His first stab at a solution was with a brand-new invention credited to the Varian brothers[30]of Stanford. They had taken the same sort of velocity-modulated tube[31] disclosed by Hahn and Metcalf of GE, and called it a Klystron, beating GE to the greco-Schenectady name game. GE had developed several such devices, calling them VEMOs (for velocity-modulated oscillators). Oliphant's klystron was a huge thing, consisting of an electron gun, an annular rhumbatron (tuned cavity past whose aperture the electrons are projected), and a repeller electrode for returning the electrons back past the rhumbatron's aperture. The thing oscillated, but the constant bombardment of the rhumbatron openings by the intense electron flow caused outgassing, and so the device needed constant pumping to maintain the vacuum. This kluge would never fit into an aircraft.

Even before the RAF radar development group (TRE) at Worth-Matravers had received Oliphant's klystron for testing, he was off in another direction, at the suggestion of two of his engineers, H.A.H. Boot and J.T. Randall. They had been scouring the literature, trying to find a better solution, and had chanced upon the magnetron work of Megaw, at GEC (British General Electric branch). Megaw was the chap who had been convinced by Posthumus, of Philips, of the correct operating principles of the multi-anode magnetron. They also had before them the book by Okabe, and in it was the

[30]Varian, Russell H. and S.F. Varian, *Journal of Applied Physics*, Vol. 10, pp 321ff, May, 1939.
[31]Hahn, W.C. and G.F. Metcalf, *Proc. I.R.E.*, Vol. 27, No. 2, pp. 106ff, Feb., 1939.

drawing and reference to Samuel's magnetron having four cylindrical cavities. Quickly they obtained a copy of Samuel's patent, and the paper by Hansen, which related cavity shape and size to resonant frequency. Realizing that Posthumus had succeeded in achieving oscillations at sufficiently short wavelengths with six anode segments, Boot designed the cavities needed for a six-cavity magnetron. A Colt .44-caliber pistol cylinder is reported to have been the drill jig Boot used to drill out the solid copper anode block. Rather than worry with the very large glass-to-metal welds needed, Boot and Randall decided to use wax seals between the end plates and the copper cavity assembly. A small cathode was used, not unlike that in Samuel's patent drawing. The whole device was forced between the poles of an electromagnet and was pumped down. To get the oscillation energy out of the magnetron, Randall had suggested using a hairpin turn of wire in one of the cavities, similar to the way energy was extracted from the rhumbatron in the earlier klystron. He brought out the cathode heater leads centered over one of the cavities to avoid disturbing the oscillating field in the cavity.

On 21 February, 1940, they tested the magnetron, obtaining 400 watts cw from it at a wavelength of 9.8 centimeters. Megaw was immediately contacted, and he participated in the conversion of the device to a more capable form. Megaw had learned from the French to use a very large cathode, able to withstand the back-bombardment by electrons, and he made the unit more compact, able to fit between the poles of a permanent magnet. Megaw also showed Boot the gold ring seal technique for bonding the end-plates to the cavity block. The cavity block was again machined using the Colt revolver cylinder as a drill jig.[32] By May, 1940, a 10-cm radar using one of these magnetrons detected a submarine periscope at a range of over six miles.

By September, Megaw and the group at Wembley had changed over to an eight-cavity magnetron, to allow use of a still larger diameter cathode. This extended the life of the tube significantly. This is the model brought to America by the Tizard Mission.

7. Further Developments

Lest the reader believe that all the magnetron development ended with the Tizard visit, consider the following.

Before the original British magnetron brought to America was in mass production, a new development was hurried to Bell Labs and Western Electric

[32]Brittain, J.E., *Physics Today*, July, 1985, p. 67, American Institute of Physics.

by the British. They had discovered the same problem with the multicavity magnetron as had been found by Posthumus at far lower frequencies. The device would shift modes, altering, slightly, its output signal frequency. This would detune the radar transmitter, relative to the receiver, and would behave just like a burned-out magnetron. The British had discovered that the correct mode could be forced out of the device if anode segments intended to be at like potentials were tied together by heavy straps, compelling the cavities to operate in synchronism, in the desired mode. Thus was born the "strapped" magnetron, the type used for the rest of the war in radar transmitters.

And the lowly split-anode magnetron also received another life. GE also realized, through wartime research, that the multicavity magnetron could operate in any of N-1 modes, where N is the number of cavities. Thus, an 8-cavity anode could operate in 7 different modes, each having a different frequency. For true wide-band tunable work, then the most stable magnetron would be a two-cavity (or two-segment) anode magnetron. So, when the US effort began to look not only at radar, but at anti-radar, they needed a powerful jamming transmitter able to be tuned to whatever frequency on which the enemy's radar operated. The GE lab, under Hull, started a large development effort at high-powered split-anode magnetrons, some tunable over tremendous frequency ranges, others restricted to a given radar band. Figure 10 shows a cut-away photo of one of these magnetrons, using an internal-tuned circuit made of copper tubing, through which water was pumped, for cooling. These split-anode magnetrons found use in the "Carpet" and "Rug" jammers of 1942-46 which played a large part in neutralizing German and Japanese home-defense radars.

8. Summary

The story of just how the multi-cavity magnetron was developed is intricate, because it involved many players, each bringing a piece of the puzzle to the attention of the catalytic efforts of Oliphant's assistants, Boot and Randall, of England.

GE's Hull, of course, first invented the crossed-field magnetron. Bell Labs' Samuel began bringing the tuned circuits for triodes into the tube envelopes, themselves, paving the way for RCA's Kilgore and Linder to put the tuned circuits entirely within the magnetrons they developed.

Then, Samuel applied his triode work to the magnetron, and patented a magnetron with four cavities surrounding the cathode, but Bell Labs never capitalized on this invention.

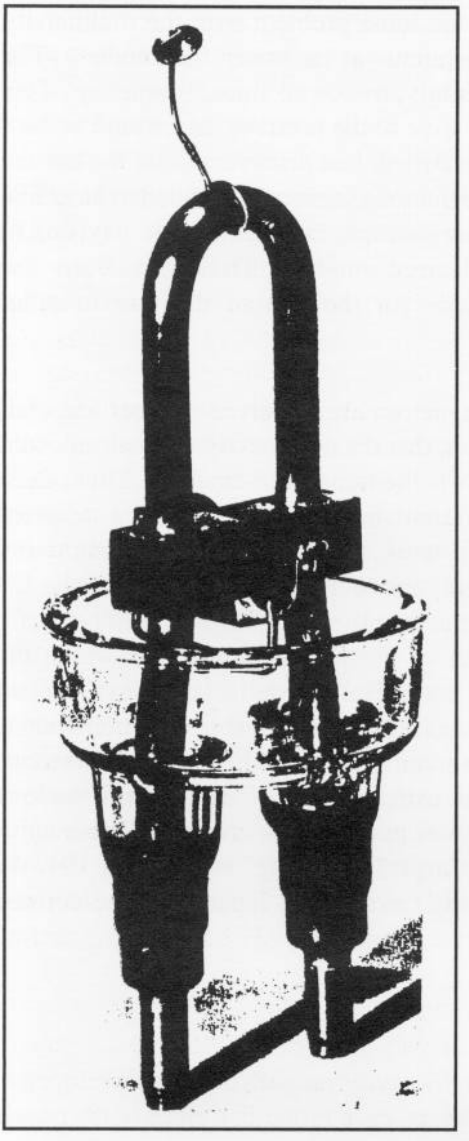

Figure 10. GE internal-tuned-circuit split-anode magnetron used in US jammers. (Envelope removed)

Kinjiro Okabe, in Japan, explained the various modes of oscillation able to be assumed by the split-anode magnetrons of the day, and he recognized Samuel's four-cavity invention as one having "...novel features.." Okabe might have developed a four-cavity anode magnetron in Japan before Boot and Randall, but I am not convinced of it, just as I am not convinced that the Soviets also invented the same magnetron several months before Boot and Randall.

The Dutchman, Posthumus, must share in the credit for showing Boot and Randall the way. He explained the only correct way magnetrons operate,

in the rotating-field, or spoked-wheel mode, at least those magnetrons capable of transmitter use in radars. Finally, the earlier work done by the Oliphant group on their version of the Varian klyston showed them how to use rhumbatrons, or tuned cavities.

Without all these contributions, Oliphant, Boot, and Randall would not have succeeded when they did. It is doubtful that Bell Labs would have reexamined Samuel's 1937 work on the multicavity magnetron, since they had him fully engaged in the invention of practical T/R (duplexer) units for radars, also destined to be important to the overall development of airborne radars. Bell Labs' Fisk, Hagstrum, and Hartman give no indication, in their famous paper on magnetron development[33], that Samuel's invention had been pursued beyond a prototype model. Thus, microwave radar would have been developed, most surely, but probably considerably later in the war, and, likely at the cost of Great Britain, herself. Without Allied airborne intercept radar to help the Beaufighters and Mosquitoes shoot them down, German bombers would have multiplied their efforts in night operations, and might have vanquished Britain.

9. Acknowledgements

The author thanks AWA's Alan Douglas, who found two references to Okabe's work in his library, John Anderson, of the GE Hall of History, Schenectady, NY, who searched for illustrations of wartime GE magnetrons, AWA's Lauren Peckham for lending his photograph of an old GE magnetron, and Bob Benson, of NASA Goddard, for lending me his copy of *The Radioscientist*. Also, a great measure of thanks is due Marty Minzell, of the Mid Atlantic Antique Radio Club, who found for me the 1937 book on Magnetrons by Kinjiro Okabe.

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[33]Fisk, J.B., H.D.Hagstrum, and P.L.Hartman, *Bell Sys Tech Journal*, Vol 25, No. 2, entire issue (1946).

Edwin (Ed) Lyon
Myersville, MD

When not engaged in his favorite activities, digging into the workings of an old wireless set and researching the background of the set and its builder, Ed earns a living as a Senior Technical Advisor at SRI International, developing over-the-horizon (OTH) radar systems. He is one of the early researchers and inventors of the modern classes of these radars. An avid writer, he has

authored about 250 papers and reports on radar, countermeasures, flight simulation, and nuclear reactors. He has several patents in electronics and rocket propulsion.

But his favorite work is discovering and documenting history - the history of radio, of radar, and of radar countermeasures (or anti-radar). He is a strong advocate of the axiom which holds that those who disdain history are often found repeating it. He has written about 120 papers and articles about the history and technology of radio and radar in the pursuit of the subject. His favorite radio history subject is the military role in early radio. His own history in radio goes back to 1940, when he made his first radio, a crystal set patterned from the design given in the Official Boy Scout Manual.

Ed is accompanied on his visits to AWA meets, hamfests, and museums by his wife of 42 years, Millie. Together they have collected about 100 historically significant radios and major components, and some 40 radios having distinctive cabinet designs (Millie's interests).

FRITZ LOWENSTEIN

THE FORGOTTEN MAN OF THE VACUUM TUBE

By
Brother Patrick Dowd, W2GK
Bronx, N.Y.

Fritz Lowenstein, the originator of the use of negative grid bias, unfortunately has received only a casual mention in radio reference books. Yet he played a vital role in helping to make the de Forest Audion come of age as a practical electronic amplifier. He shares this honor with H. D. Arnold and other Western Electric engineers who improved the vacuum, the filament, and ruggedized and refined the element structure of the Audion. The following is a presentation of available documents supporting the contributions of Fritz Lowenstein and the many difficulties he encountered in his pursuit of patent recognition.

Little is known about his early life and very few specific dates are available regarding the known events in his life. Educated guesses have had to be made in placing some of these events in chronological order.

He received his early engineering training in Europe, earning advanced degrees in engineering and physics from several Austrian universities. Before leaving Europe he worked with Sir William Crookes on electrical discharges through gases. On immigrating to America he signed on as an engineering assistant to Nikola Tesla and worked with him in his Colorado Springs Radio Power Transmission experiments.[1] In 1899, when Tesla was setting up his new laboratory, he wrote to George H. Scherff[2] in New York asking him to send Fritz Lowenstein, his young assistant, west, "He must be here to oversee construction and locate equipment.[3]" When Lowenstein completed work in Colorado, he returned to Germany. In 1902, when Tesla was setting up another laboratory at Wardenclyffe, L.I., N.Y., he sent Lowenstein his return fare and was joined by him shortly thereafter.[4] Three years later their relationship was terminated for financial reasons.[5]

In 1905, upon leaving Tesla's employ, Lowenstein opened an office and laboratory at 125 West 32nd Street, New York City, and went into business for himself as a consulting and research engineer.[6]

In 1907 John Stone Stone, president of The Telegraph and Telephone Company of Boston, Mass., founded the Society of Wireless Telegraph

Engineers. He originally intended membership to be limited to his company but later expanded it to include other individuals working in wireless. Fritz Lowenstein became a member. On May 13, 1912, the S.W.T.E. merged with the Wireless Institute of New York City to form the Institute of Radio Engineers. The members of both organizations became charter members of the I.R.E. Fritz Lowenstein became the first vice president and a member of the board of directors of the new organization.[7] He was the president of the S.W.T.E. in 1912 when this merger took place.[8]

In the winter of 1909-1910 he made a move that would prove most significant in his quest for a practical telephone repeater and the eventual development of his negative grid bias patent. He was hired by the president of The Radio Telephone Company of Newark, N.J. (a de Forest subsidiary), as a consulting engineer.[9] While working there he first became aware of the existence of the de Forest Audion and soon realized its potential as a telephone repeater. He lost no time in experimenting extensively with the Audion. Lowenstein remained with the company until it went bankrupt in late 1910 or early 1911. The company, together with other de Forest companies, went on the auction block on March 11, 1911,[10] and it was probably at this time that he opened his new office and laboratory.

> It was in a laboratory at 115 Nassau Street in New York City, during the winter of 1911-12, that developments of great scientific importance took place. These developments, which included a telephone repeater and a vacuum tube radiotelephone transmitter, were made under the leadership of Fritz Lowenstein.[11]

On May 11, 1911,[12] shortly after setting up his new office, he was retained by John Hays Hammond, Jr., of Gloucester, Mass., as a consultant on the work Hammond was doing on radio-controlled torpedoes and other remotely controlled devices. Lowenstein brought to his new work his recently acquired knowledge of the Audion. In mid-summer, Benjamin F. Miessner, recently honorably discharged from the Navy, entered the employ of Hammond on the recommendation of Lowenstein. It was arranged that Miessner should work at Gloucester during the summer and spend the rest of the year at Lowenstein's laboratory, dividing his time between Lowenstein's own projects and those sponsored by Hammond.[13] It was agreed at the time that Hammond and Lowenstein would split the cost of Miessner's salary ($130 per month) between them.[14] Miessner's assignment with Lowenstein was to assist him in his own research and development work on vacuum tubes, audio amplifiers for telephone-repeater use, and the design and construction of radio transmitters and receivers that he was carrying on under a contract with the Navy. The receivers, incidently, contained the "cat's-whisker" detector that had been patented by Miessner.[15]

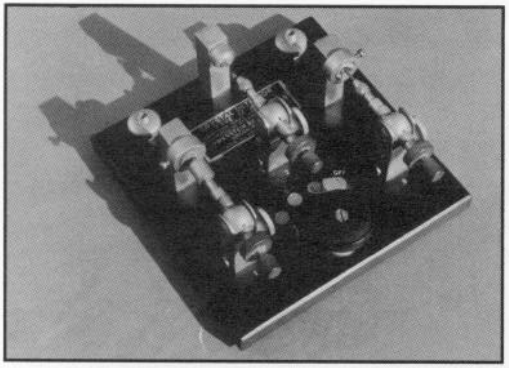

Figure 1. Lowenstein Radio Company Triple Crystal Detector, Type SE-183A, made for the Navy Department - Bureau of Steam Engineering, 1918.

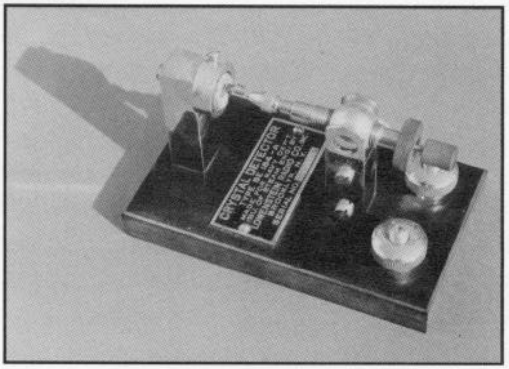

Figure 2. Another Lowenstein product, Crystal Detector Type SE-184A, also manufactured for the Navy Department in 1918. Photos courtesy of James Kreuzer.

In 1909, Benjamin F. Miessner, after graduating from the general electrical and wireless schools at the Brooklyn Navy Yard, was assigned to the U.S. Navy Radio Station in Washington, D.C. A year before his release from the Navy, he served as Radio Officer, 1st. Class, aboard the U.S.S. South Carolina.[16] After joining Hammond and Lowenstein, he did much of the construction work for their projects. A competent radio pioneer in his own right, with 150 registered U.S. patents, he credits Lowenstein for much of his success. He deserves special mention here because he is responsible for much of what we know about many of the events in Fritz Lowenstein's life. Miessner lost no opportunity, in his writings and talks in later life, to give credit to his mentor, "Whose great contributions deserve recognition."[17]

While Lowenstein was still in his employ, Hammond rented the Poulsen 30-kW arc transmitter at Arlington, Virginia, from C.F. Elwell (of the Federal Telegraph Company), for $250/month. Both men experimented with the transmitter for some time.[18]

In March of 1915, Lowenstein had a commentary on "Radio Frequency Changers" published in the *I.R.E. Proceedings*. As we shall see later, this was a subject in which he was keenly interested. In Dec., 1915, he presented two papers before the I.R.E., one on "Capacities" and the other on "The Mechanism of Radiation and Propagation of Radio Waves." These papers were printed in the *I.R.E. Proceedings* in Feb. and June of 1916.

Early in his career he formed the Lowenstein Radio Company and contracted to supply quenched-gap spark transmitters to the U.S. Navy, both prior to and during WW I. He held several patents on these transmitters.[19] There are at least eleven known types of transmitters, all of the quenched-gap spark type in the 1-kW, 2-kW and 10-kW class,[20] and two types of crystal detectors—one a triple detector—in the possession of a radio collector,[21] and several other types of crystal detectors listed in the files of a radio historian,[22] that were made for the Navy. The *Electrical World* in their March 2, 1918 issue announced that the Lowenstein Radio Company of New York, N.Y., had been incorporated with a capital stock of $500,000 by F. Lowenstein, 397 Bridge Street, Brooklyn, N.Y. and A. Harris of Newark, N.J. In a brochure that was distributed by the company after the war, announcing their entrance into the commercial radio field, it was stated that the company manufactured approximately $700,000 worth of apparatus per annum for the Navy during the war.[23]

On April 24, 1912 Fritz Lowenstein applied for a U.S. patent on a "telephone relay" (Application No. 692,828), which embodied the use of a battery to hold the grid of the ion controller at a potential which was negative with respect to the filament. It was first deemed to be unpatentable and no action was taken by the Patent Examiner. On September 8, 1915, he resubmitted his patent application accompanied by an affidavit in which he describes the history of the development of the negative grid bias patent. The complete affidavit follows:[24]

AFFIDAVIT

City of Washington) ss:
District of Columbia)

Fritz Lowenstein, of Brooklyn, New York, the above named applicant, being duly sworn, deposes and says as follows:

I am an electrical engineer by training and profession and for the last seventeen years have been engaged in practical work as well as research in various electrical lines, particularly in wireless telegraphy and allied subjects. I conceived the invention set forth in present claims 1, 2 and 3 of my application, above identified, in the latter part of the year 1906 under the following circumstances:

During November, 1906, I was engaged in certain experiments involving the use of a Cooper-Hewitt mercury rectifier. This work was carried on at my laboratory which was then located at 125 West 32nd Street, New York City. In the course of these experiments I happened to discover

that by touching a certain portion of the connected anode arm of the evacuated rectifier tube, the current through the rectifier was interrupted as was evidenced by the fact that the anode arm ceased to glow. This phenomenon impressed me as important and on Nov. 28, 1906, I recorded my observations in a regular book of records kept for such purposes. A photographic copy of this entry of Nov. 28, 1906 is attached hereto as exhibit A. This entry shows diagrammatically the arrangment of circuits in the experimental apparatus at the time I observed the above phenomenon.

On or about the same date it occurred to me that the observed phenomenon could be usefully applied in various connections and among the other things I thought of its use as a telephone repeater. On the reverse siding of the original page of my record book corresponding to Exhibit A, I noted a number of these uses, including their adaptation to a telephone repeater. A photographic reproduction of said reverse side being attached hereto as Exhibit B.

(Author's note:
Exhibits A, B and C not available.)

I immediately conducted further tests with respect to this phenomenon and soon discovered that the effect produced by touching the anode arm of the rectifier differed considerably depending upon where I stood in the static field conditioned by the circuit wires of the apparatus. Thus I found that when standing in one position, current through the rectifier would be totally interrupted when I touched the anode arm. Sometimes, also, when the rectifier tube was under potential, but no current was flowing, if I touched the anode arm the current was thereby started.

(Author's Note:
The schematic diagram was located here in the
original document. Refer to the next page.)

The schematic diagram shown, entitled "telephone relay," can be considered a telephone instument or terminal: (1,2) are the line connections; (4) is the telephone ringer; (6,9) are the primary and secondary of a telephone induction coil; (3,7,11) are the elements of a hookswitch which operates when the receiver is removed or replaced; (8) is the telephone transmitter or microphone; (12,13) are the primary and secondary of a transformer connected to the Audion amplifier circuit; (22,23) are the primary and secondary of the plate transformer, feeding the telephone receiver. The other elements are part of the standard Audion amplifier circuit.[26]

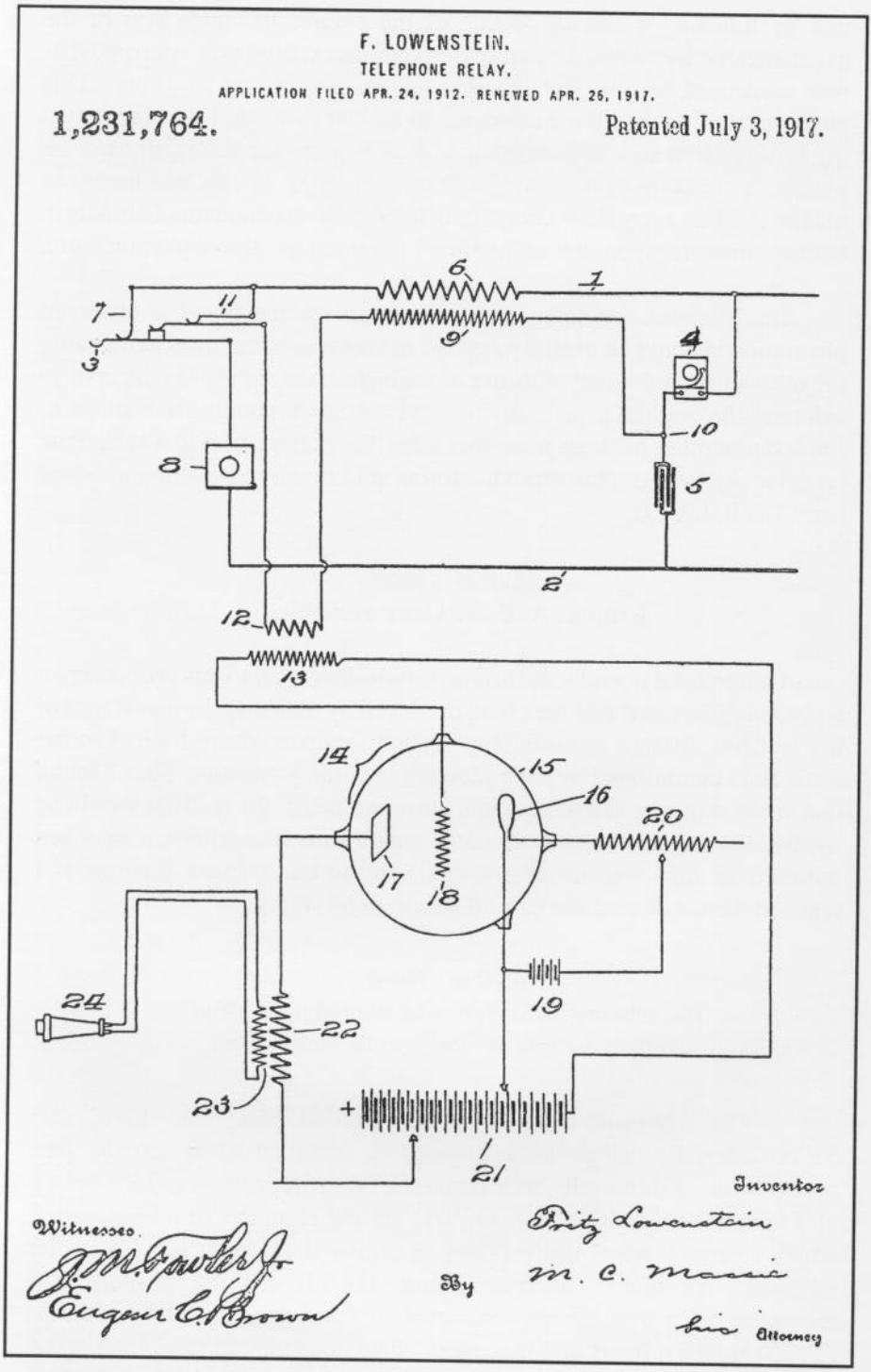

Figure 3. Lowenstein's patent diagram[25]

My original discovery of the phenomenon noted, was made in the presence of W.T. Hoofnagle, then of Whitestone, L.I., now of Glen Ridge, N.J., and William Maxfield, of Brooklyn, N.Y., since deceased. On or shortly after the date of my discovery I carefully explained my observations to Mr. Hoofnagle and disclosed to him my idea that this phenomenon could be made use of practically in connection with telephone repeaters or relays.

Before proceeding to develop the invention practically and to embody the principles of the same in complete apparatus which would necessarily involve considerable time and expense, I desired to investigate more fully the theory underlying the phenomenon above described and thereby to be able to perfect suitable apparatus for the purpose more readily. I accordingly took a course of lectures under Dr. Charles P. Steinmetz at Brooklyn Polytechnic Institute. While pursuing these investigations, I was also busily engaged with my regular business, particularly in manufacturing wireless telegraph apparatus which I had contracted to furnish the U.S. Government for use on battleships of the Navy. Consequently it was impossible for me to devote my whole time and attention to the telephone invention, but I kept it in mind continually and gave it all the time I could spare in the way of study and experiments.

In the winter of 1909-1910 I did some work as consulting expert to the President of the Radio Telephone Company, of Newark, N.J., and in their shop and at that time I constructed and assembled an operative telephone system of which the receiving end was arranged substantially as shown in the drawings of my above application, except that the grid 18 was simply connected to one side of the filament 16, i.e., at the same potential as the filament. A print of said drawings is hereunto attached as Exhibit C. The talking line of this telephone system was about 60 feet in length. In order to test the invention under the most adverse circumstances, a resistance was inserted at the point X (Exhibit C), of such magnitude that absolutely nothing could be heard in the receiver of the usual telephone system placed between the points Y and Z; the ordinary receiver was replaced by the ion controller, the talk was loud and perfectly clear. To enable a ready comparison of the two operating conditions, a switch was arranged to cut into the system either the ordinary telephone receiver or the ion controller relay.

The results of this actual construction and successful operation of the invention were immediately communicated to Mr. Hoofnagle and to a number of others.

In 1911 I did further work on the invention in the way of perfecting certain details thereof. In particular, I installed a Geissler mercury pump and constructed vacuum tubes of different shapes and dimensions in order to determine those most advantageous for my purposes. At this time the invention was also in practical use on a number of occasions, the arrangement of the circuits being substantially the same as in the 60-foot system previously set up at Newark, N.J. I talked from my office (then at 115 Nassau Street N.Y.C.) to Gloucester, Mass., Washington, D.C., Chicago, Ill., and various other points, the ion-controller receiver being arranged for connection to the lines of the New York Telephone Company by a quick-change switch which could also be operated, as before described, to cut in the usual telephone receiver alternatively for purposes of comparison. The ion-controller receiver of the invention showed consistently, results far superior to those obtainable with the ordinary telephone receiver.

The different tests conducted in 1911 were either witnessed or participated in by a number of people, among whom may be mentioned John Hays Hammond, Jr., of Gloucester, Mass. Harris Hammond (brother), of New York City, Louis Engelhorn, of New York City, F.A. Kolster, then of New York City, now of Washington, D.C., and W.T. Hoofnagle, above mentioned.

The apparatus employed in the 1911 tests were constructed with the aid of Benjamin F. Miessner (now at Purdue, Indiana) and George H. Scherff, of New York City.

In a talk in 1911 with Louis Engelhorn at the Chicago end of the line, and Harris Hammond and myself at the New York end, we employed a condenser in the grid circuit and found that the talk over the line was poor, the current through the controller tending to choke or stop. I found that this could be remedied readily by touching the grid binding post repeatedly to discharge the grid and to open up the talk. This gave me the idea of connecting the grid to a point ultranegative in potential relative to the filament. Such connection of the grid was actually made in the latter part of 1911 and was found to be a very substantial improvement. This specific arrangement forms the subject matter of specific claims of my application above identified.

I do not know and do not believe that my said application has been in public use or on sale in this country, or patented or described in a printed publication in this or any foreign country, for more than two

years prior to my said application; and I have never abandoned the invention.

Fritz Lowenstein

Subscribed and sworn to before me this 8th day of Sept., 1915.

SEAL Eugene H. McLachlen, Notary Public

(THE FINAL SEVEN CLAIMS OF THE PATENT APPLICATION ARE LISTED AT THE END OF THIS ARTICLE).

PAPER NO. 9.

Rejection dated October 11, 1915.

Claims 1, 2 and 3 rejected on de Forest 995,126, of record, or

Stone, 884,110, April 7th, 1908, 250-27.

The affidavit under Rule 75 does not antedate the de Forest patent or that of Stone, as there appears to be no indication that the invention was made until 1911. In fact the affidavit clearly indicates that all that was done before consisted in somewhat general experiments which lead to finally completing the invention in 1911. There is nothing in the affidavit to even indicate that applicant had prior to that time any conception of the invention defined in the claims. So far as claims 1, 2 and 3 are concerned, they define nothing more than the ordinary Audion as used by de Forest and as shown in the Stone patent and nothing patentable is expressed in these claims.

Claims 4, 5 and 6 bring out the idea of making the grid ultranegative with respect to the filament. In the first place, experience has shown that in use the Audion, such as shown in the de Forest patent, acquires a negative charge, due principally to the discharge of negative ions from the cathode. Hence there is a means in de Forest's Audion for making the grid ultranegative with respect to the cathode. In Stone this situation

was treated as a defect and was overcome by including a source in the grid circuit which rendered the grid positive with respect to the cathode. Stone appears to have been seeking to overcome the same defect as applicant claims to have found and remedied in the de Forest Audion and it does not appear that it is of any material difference whether the grid be made positive or negative with respect to the cathode and it is not believed to involve invention to change the polarity of the source of current 'z' in the patent to Stone so as to render the charge upon the grid negative instead of positive. It should also be noted that the affidavit under Rule 75 does not overcome the reference to Von Lieben so far as the subject matter of Claim 4, 5 and 6 is concerned, as the affidavit clearly states that the arrangement of a source in the grid circuit was not made until the latter part of 1911, whereas the Von Lieben application was filed Jan. 30, 1911, which is prior to this time.

The claims are all rejected.

Wm. A. Kinnan
Examiner, Div. XVI

The subsequent file record shows that in 1916 Lowenstein had a personal interview with the Patent Examiner and offered to demonstrate experimentally the effectiveness of rendering the grid negative, and at the same time new claims were entered clarifying the negative grid feature (Amendment of July 5, 1916.)

Without further rejection the application was passed for issue Oct. 16, 1916.

On April 28, 1917, a request for renewal was filed because of nonpayment of final fee. There was entered an amendment of April 26, 1917, making small changes in the text. Claim 1 was replaced by a new claim 1 and additional claims entered corresponding to printed Nos. 4, 5, 6 and 7.

The application passed for issue on May 4, 1917. The patent was granted July 3, 1917 as No. 1,231,764.

It appears that Fritz Lowenstein is not the only inventor of negative grid bias in vacuum tubes, but is actually the first person to have taken de Forest's three-element Audion, which for years had been known only as a sensitive wireless detector, and make it operate as a telephone amplifier.

De Forest first made the Audion into an audio frequency amplifier at the end of July, 1912, and he and Stone demonstrated it to the telephone people, in the Western Electric laboratories, in October, 1912. As de Forest demonstrated it, the Audion still had in it the grid condenser of its radio detector days which greatly limited its operation as a voice-frequency amplifier by causing it to block. Apparently de Forest did not fully understand his amplifier.

It appears that Fritz Lowenstein was experimenting with the Audion as a telephone amplifier, using a negative 'C' battery, toward the end of 1911. Frederick A. Kolster, who was with Lowenstein at the time, mentioned that when he left Lowenstein and went to the Bureau of Standards on Dec. 1, 1911, Lowenstein had been working on the 'C' battery development. It also appears from subsequent testimony that these experiments made use of an audio frequency step-up input transformer and high impedance telephone receivers in the output.[27]

It would seem, from the records, that the Telephone Company's learning of Fritz Lowenstein's invention was their first introduction to the Audion, as shown in the company's patent file No. 200,513 - Fritz Lowenstein - as follows:[28]

EVENT	REFERENCE
In Dec., 1911, John Hays Hammond, Jr., came to see Mr. Carty and told him of an invention by F. Lowenstein described as an Ion Controller.	*Letter entitled "Ion Controller," F.B. Jewett to Fritz Lowenstein, Dec. 20, 1911*
Lowenstein and Hammond, Jr., brought their new repeater to the office of F.B. Jewett, Transmission Protection Engineer, A.T. & T. Co., and demonstrated it in a sealed wooden box* on Jan. 27, 1912. They did not disclose the precise nature of the thing in the box.	*F. B. Jewett's memorandum dated Feb. 3, 1912.*
June 1912, Lowenstein disclosed the fundamental idea to Jewett and Blackwell, that of controlling an ionic stream by means of a static field produced or varied by the potential at the end of the incoming line. The electrostatic control element is maintained at a potential somewhat lower than that of the cathode by means of an auxiliary ("C") battery, the tendency of the static field produced thereby being to cut down the ionic discharge. If this potential is sufficiently high, the ionic discharge can be completely stopped off. Lowenstein explains that in most of his experiments he used ordinary Audion tubes purchased from wireless suppliers. He drew a sketch showing both the mercury arc and the	*F. B. Jewett's letter to J.J. Carty, June 29, 1912, and enclosed statement and sketch.* **Note: The "black box" was 12x6x5 inches in size and contained an Audion, "A", "B" & "C" dry cell batteries, a rheostat for filament current con-*

Audion adaptation of the control. The sketch shows both input and output transformers.

trol and a rotary switch to vary the negative grid bias voltage up to 15 volts. Provision was made for externally adding additional "C" batteries. The box was lined with lead to prevent X-ray examination. It was then padlocked. Contact was made to the box by "In" - "Out" terminals.[29]

July 2, 1912, copy of the above letter sent to our Patent Counsels, T.D. Lockwood in Boston and to Charles Neave in N.Y.

July 3, 1912, Charles Neave says to Carty "It does not seem to me that one could obtain as good results from this form of repeater as with the form upon which the Western Electric Company has been working" (mercury vapor). He points out that Lieben in his German patent speaks of acting upon the cathode stream by a magnetic or electrostatic field.

July 31, 1912, Carty writes to Lowenstein saying that, "You have already given enough indication of its nature to enable us to say in which class it falls," and pointing out that, "to make up our mind whether the invention is of interest or not it will be necessary that our people have full understanding of it," and, "we have ourselves done work along similar lines."

Jewett's letter to Gherardi of Sept. 25, 1912.

Mr. Hammond and Mr. Lowenstein came to see Mr. Jewett on Sept. 24, 1912, and offered the repeater invention on the basis of Lowenstein's entering the employ of the company to perfect it. Dr. Jewett sought to separate the two propositions and the understanding was that they would disclose their device completely and submit apparatus for test, and also that Mr. Lowenstein would state in writing his proposal looking toward employment.

Nov. 20, 1912, Jewett tells Lowenstein on the telephone: that until Mr. Hammond and he presented their device for examination they would not know whether there is anything which they would wish to consider employing him to work upon.

Jewett's letter to Carty, Nov. 23, 1912.

Jan. 26, 1913, there was made the first complete disclosure and demonstration. This was made by Mr. Lowenstein's as-

Colpitt's report to Jewett, Jan. 31, 1913

sistant Mr. G. Schreff, during Mr. Lowenstein's absence on a trip abroad, made before Mr. Colpitts and Mr. Richards of the Western Electric Company. Colpitts finds that "the element itself is the ordinary Audion, as previously disclosed to us. The main difference between the Lowenstein disclosure and the Stone-de Forest disclosure lies in the circuit," de Forest having a grid condenser and Lowenstein a series battery in the grid circuit, "a source of direct potential between the heated cathode and the grid so as to make the grid negative in respect to the cathode." Colpitts says, "On our part we were as careful as possible not to allow Mr. Schreff to get the idea that we were at all familiar with the Audion." He adds that, "the whole matter of using direct current potential in the grid circuit is being broadly considered by us."

accompanied by a drawing made by Mr. Schref and one made by him.

Jewett tells Carty of this disclosure saying, "So far as I see there is nothing in what has been disclosed to us that is of particular value in the light of the de Forest and von Lieben patents." and, "It is certain that the thing we now have is in itself of no value to us, nor have we learned anything from the physical disclosure which they have made."

Letter of Feb. 5, 1913.

Copy of Jewett's letter sent to Lockwood, saying that the repeater element used by Lowenstein is that of de Forest and Stone and that physically the disclosures have added nothing to their knowledge of this type of repeater.

February 18, 1913.

Lockwood says he agrees there is nothing more to do pending the issuance of the patent.

March 12, 1913.

On April 18, 1913, Hammond and Lowenstein came in and had lunch with Jewett, and it was arranged that Mr. Lockwood will be given the patent papers by their Patent Attorney, Mr. Massie.

Jewett to Gherardi, April 19, 1913.

Lockwood reports upon the Lowenstein patent application, Serial No. 692,828, filed April 24, 1912. He finds that the operation of the Lowenstein device would infringe a number of de Forest's patents, and concludes, "that the invention of Lowenstein is without patentable novelty, and is controlled by a number of prior patents..."I do not see that the Lowenstein people really have anything to sell."

Lockwood to Carty, May 20, 1913.

Colpitts and Jewett go over the Hammond and Lowenstein papers and consider that, "the next move should be for somebody - either Mr. Carty or Mr. Lockwood - to advise Mr. Hammond that we are not interested.

Jewett to Gherardi, May 27, 1913.

Lockwood gives this same advice to Carty.	*Memorandum of June 12, 1913.*
Lowenstein asks to have has patent papers returned.	*His letter to Jewett of May 20, 1914.*
Lockwood returns to Lowenstein the papers he had received from Mr. Massie.	*Letter to Carty, June 3, 1914*

On September 6, 1918, shortly before the end of WW I and over a year after the patent was issued, A.T. & T. purchased the Loewnstein negative grid patent rights for the amazing sum of $150,000. This was a rather generous amount to pay for what the Telephone Company could not see that there was "anything to sell." This sum is all the more remarkable when you consider that A.T.& T. had obtained the telephone rights to the de Forest Audion for only $50,000. For years after this event, Lowenstein carried a photostatic copy of this check about with him and showed it to any and all interested parties.[30]

It is possible that after the Lowenstein patent was rejected on Oct. 11, 1915, that A.T.& T. may have been using the negative grid concept in the interim, especially in their long distance lines, and the inflated price paid for the patent rights may have included payment for this use.

Milton Lowenstein, Fritz's son, states: "There were two basic parts to the "C" bias patent: one for use in the telephone field, the rights sold to the A.T. & T. for $150,000; the other for general use, etc., was bought by William Dubilier from my father's estate for a $25,000 debt (approx.) and resold to RCA for an undisclosed amount (I was told by other than Dubilier it was in the millions). In this package deal from the estate, Dubilier also received the logarithmic condenser (Lowenstein - U.S. Patent No. 1,258,423, March 5, 1918) which was sold to the Scoville Mfg. Company and was, and still is, the

AMERICAN TELEPHONE AND TELEGRAPH COMPANY
NEW YORK SEP 6 1918 19 No 2320
PAY TO THE ORDER OF Fritz Lowenstein $150000
$150000 AND 00 CTS DOLLARS
CHASE NATIONAL BANK NEW YORK
American Telephone and Telegraph Company
Assistant Treasurer

Figure 4. A copy of A.T. & T.'s check to Fritz Lowenstein.[31]

basis of tuning a radio freqency circuit to avoid crowding all the high frequency stations in a small portion of the 180 deg. arc..... In the late 40s or early 50s I saw David Sarnoff in his RCA office and we reminisced about the early days of radio, when I was still a child, and he remarked that one of the most important patent acquisitions by RCA was the "C" bias rights..... During the World War I years the Marconi Company, the Wireless Specialty Company and one other company, which I can not recall, built 1/2-kW and 2-kW quenched-gap spark transmitters for the U.S. Navy in accordance with my father's patents and design..... During these years, Hill and Clark, two Navy inspecters, spent some time at the Lowenstein Radio Company, 397 Bridge Street, Brooklyn, N.Y., then returned to Washington, D.C., and filed patent claims for the "Wave Changer" (another of my father's inventions.) This patent wound up in court during the early 20s and due to my father's untimely death, in May of 1922, there was not the proper guidance to bring this interference case to a successful conclusion."[32]

Benjamin Miessner, referring to his notebook entries dated Feb. 27 to 29, 1912, while he was in the employ of Lowenstein, states that, "Lowenstein was the first to use the triode as an amplifier and as an af and rf oscillator, several months before de Forest, who did not succeed in turning his triode into an effective amplifier until the summer of 1912."[33] The same author, in Part 2 of a two-part article written for the November, 1961, issue of *Wire and Radio Communications*, tells of Lowenstein's work in the field of regeneration. He was a claimant, along with de Forest, Armstrong and others to the regenerative circuit.

In a news item in the August, 1931, issue of *Electronics*, comment is made on a suit brought against the Pacent Company and Sol Wallerstein, a Buffalo, N.Y. theater exhibitor, who had installed a Pacent talking-picture apparatus. A.T.& T. Company, Western Electric Company and Electrical Research Products, Inc., sued for patent infringement. Although many patent infringements were originally involved, two principal infringements deserve special note: the Lowenstein negative grid bias patent and the Colpitts, so called push-pull, patent. The Lowenstein patent was declared invalid by Judge Galston and no action was taken on the Colpitts patent since it was to expire the following February.

The Western Electric Company immediately entered an appeal from Judge Galston's decision. The validity of the Lowenstein patent was eventually upheld.[34]

Lloyd Espenschied, in a letter to Gaston Burridge, gives us a more personal view of Lowenstein: "My period of acquaintance with him was from 1909-1912 through the Wireless Institute here in New York, and continued to

about 1920 through the succeeding society, the I.R.E. Just when he died, I do not recall, but it was all too soon, for I had a high regard for him. He was of pleasing personality, inclined to be diffident, of high character, and an excellent creative kind of engineer..... Fritz Lowenstein, to my mind, never has received appropriate recognition..... The person who at one time was his financial backer, John Hays Hammond, Jr., of Hammond Reseach Corp., Gloucester, Mass., has said that his early heroes were Tesla and Lowenstein."[35]

Fritz Lowenstein played a substantial role in the early days of radio development, yet he receives minimal credit for his many contributions. His name is not exactly a household word. He is truly one of the unsung heroes of the radio pioneers.

ACKNOWLEDGEMENTS

A major part of the above article was taken from the correspondence and notes of Lloyd Espenschied and Gerry Tyne, through the courtesy of Gertrude Tyne. I would also like to acknowledge the contributions of fellow A.W.A. members: Alan Douglas, Jerry Vanicek, Bruce Kelley, Ludwell Sibley, Bob Morris, Jim Kreuzer, Al Jones, Will Jensby and Elliot Sivowitch/ Smithsonian Institution.

****

THE FINAL SEVEN CLAIMS OF FRITZ LOWENSTEIN'S PATENT APPLICATION ARE LISTED BELOW:

Claim 1, Telephone apparatus comprising the combination, with a talking circuit, of a suitably energized relay circuit including an anode and a cathode separated by a conductive gap, a modulating device interposed in said gap, and electrically connected with said talking circuit, means for impressing upon said modulating device a potential more negative than that of said cathode, and a translating device arranged to be energized from said relay circuit.

Claim 2, Telephone receiving apparatus, comprising the combination with a talking circuit, of an ion controller having an anode and cathode connected in a second circuit electrically related to said talking circuit, a modulating device interposed between said anode and cathode, means for energizing said modulating device from said talking circuit and also from a source of potential which is negative with respect to said cathode, and a telephone receiver arranged to be energized from the controller circuit.

Claim 3, Telephone receiving apparatus comprising the combination, with a talking circuit, of an ionic controller having an anode and a cathode suitably spaced apart, a battery, connections from said anode and cathode to the battery, a grid electrically connected to said talking circuit and interposed between said anode and cathode, a connection from said grid to said battery, the battery connection of the grid being negative with respect to the battery connection of the cathode, and a telephone receiver arranged to be energized from the controller circuit.

Claim 4, Telephone apparatus comprising the combinations, with a talking circuit, of a cooperating circuit suitably energized and including an anode and a cathode separated by a conductive gap, a modifying or controlling device interposed between said anode and cathode and subjected to an impressed potential more negative than that of said cathode, and a third circuit energized by said cooperating circuit.

Claim 5, The combination, with an exhausted container, and an anode and cathode located therein and included in a suitably energized circuit, of a modifying or controlling device interposed between said anode and cathode, and another circuit inductively related to the first mentioned circuit.

Claim 6, The combination, with an exhausted container, and an anode and a cathode located therein and included in a suitably energized circuit, of a modifying or controlling device connected to a source of potential more negative than said cathode and adapted and arranged to influence the character of the field between said anode and cathode, and another circuit inductively related to the first mentioned circuit.

Claim 7, The combination, with an audion having its anode and cathode included in a suitably energized circuit, of means for impressing upon the audion grid a potential more negative than that of the audiòn cathode.

In witness whereof I have hereunto affixed my hand this tenth day of January, 1912.

FRITZ LOWENSTEIN

WITNESSES:

O. F. Rothen,
L. Baschang.

****

REFERENCES

1. Benjamin Miessner, *Wire and Radio Communications*, Vol. 10, October, 1961, p. 23.
2. George H. Scherff, at this time, an assistant of Tesla. He later joined Lowenstein's staff.
3. Margaret Cheney, *TESLA, Man Out Of Time*, Dorset Press, N.Y., 1981, p. 135.
4. As [3], p. 161.
5. As [3], p. 204.
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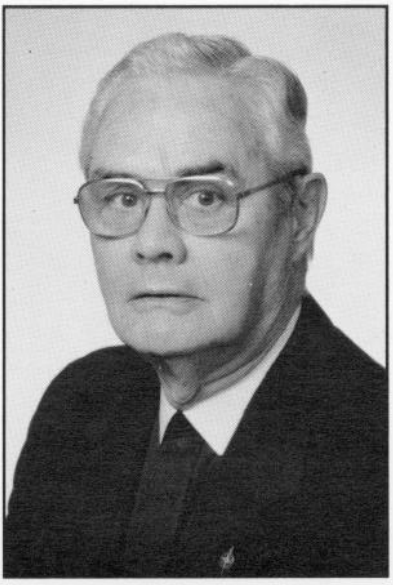
8. *Proceedings of the I.R.E.*, Vol. 1-3, 1913-1915, p. 113.
9. Affidavit of Fritz Lowenstein submitted, Sept. 8th, 1915, to the Patent Examiner, Washington, D.C. (see text).
10. Gerald F.J. Tyne, *Saga of the Vacuum Tube*, Howard M. Sams & Company, Indianapolis, IN, 1977, p. 107
11. As [1], p. 23.
12. John Hays Hammond, Jr., *Proceedings of the I.R.E.*, September, 1957, p. 1197. From The Smithsonian Instution, courtesy of Elliot Sivowitch.
13. Benjamin Miessner, *On The Early History of Radio Guidance*, San Francisco Press, 1964 p. 6.
14. As [13], p. 9.
15. As [13], p. 9.
16. As [1], p. 23.
17. As [1], p. 23.
18. Letter from C.F. Elwell to Lloyd Espenschied dated 8/21/52 (Lloyd Espenschied, formerly of the Bell Labs, is a renowned radio historian)--from the personal files of Gertrude Tyne.
19. Milton Lowenstein's letter to the editor of *Spectrum*, April 4th, 1983, from the personal files of Alan Douglas.
20. From the personal files of Ludwell Sibley.
21. From the private collection of Jim Kreuzer.
22. From the personal files of Will Jensby.
23. Howard Schrader, AWA file # Q22, 4/10/76, p. 4 of a publicity release of the Lowenstein Radio Company, distributed shortly after WW I - Courtesy of Bruce Kelley.
24. From the file wrapper of Lowenstein's patent application #692,828. Espenschied's files courtesy of Gertrude Tyne.
25. From Lowenstein's Telephone Relay (negative grid bias) patent #1,231.764, July 3, 1917.
26. Diagram description supplied by Robert M. Morris.

27. The correspondence and notes of Lloyd Espenschied, from the personal files of Gertrude Tyne.
28. As [27].
29. As [13], p. 17.
30. As [27].
31. As [23].
32. As [19].
33. As [13], p. 19
34. As [12], p. 1198
35. Correspondence - Espenschied to Burridge, November 5, 1958, Box 13, Espenschied Papers - Smithsonian Institution, courtesy of Elliot Sivowitch.

Brother Patrick Dowd, F.S.C.
Manhattan College, C.B.C.
4415 Post Road
Bronx, NY `10471-3499



Brother Pat is a retired science teacher, a twenty-year member of the Antique Wireless Association and the founder and curator of the Vacuum Tube Museum at Manhattan College, located in the Riverdale section of the Bronx, N.Y. He is the editor of the vacuum tube column of the Old Timer's Bulletin of the A.W.A. and has received both the Tyne and Houck A.W.A. awards for his contributions to vacuum tube history and preservation. He is a Fellow of the Radio Club of America and the recipient of their Ralph Batcher Memorial Award. He has been an active radio ham for almost fifty years (W2GK) and is a longtime member and past president of the North Jersey DX Asssociation.

83 YEARS OF U.S. AMATEUR LICENSING

By
Neil D. Friedman, N3DF
Boulder, Colorado

INTRODUCTION

The addition of a "no-code" VHF class of U.S. amateur radio license, with talk of reducing code requirements for HF classes, reminds us that the federal regulation of operator licensing is a dynamic process. Requirements and privileges periodically change with shifts in regulatory philosophy, the state of the radio art, and the larger culture in which ham radio exists.

Today, there are members of the Quarter Century Wireless Association (QCWA) whose amateur radio careers post-date the tumultuous "incentive licensing" debates of the 1960s. Only a relative handful of current hams experienced the "A-B-C" era of licensing that shaped amateur radio for so long prior to 1951. Lest any of the newer radio amateurs assume that the license structure has always been as it is today, a review of the history of U.S. amateur operator licensing is clearly in order.

This review is not comprehensive; it is only an overview of the history and development of amateur radio operator licensing. Band privileges are discussed only as they relate to structural changes in licensing. For length and readability purposes, license term lengths (which have increased from two to ten years), fees, renewal activity requirements, and time-in-class requirements are not treated. Further, the substantial contributions of parties other than the American Radio Relay League (ARRL - a national association of amateur radio operators) to FCC rule-making proceedings are sparsely mentioned.

THE ROOTS OF OPERATOR LICENSING

Pioneer U.S. radio operators, amateur and maritime, passed the century's first decade without any licensing requirement. Other seafaring nations, however, tested and certified shipboard operators in accordance with the Berlin Radiotelegraphic Convention of 1906 (an early use of the word "radio"). The

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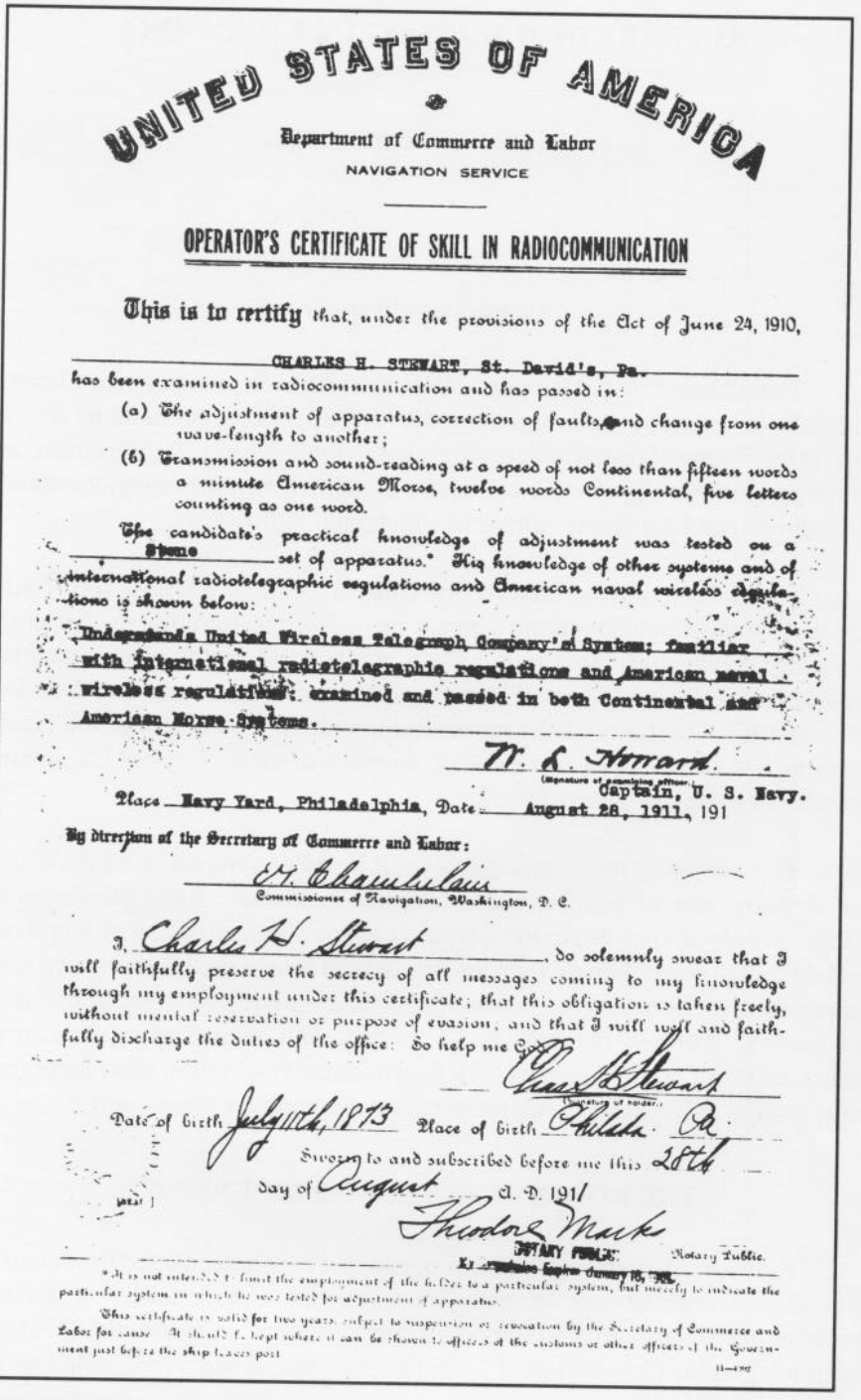
Portions of this article first appeared in the author's "Amateur Radio Licensing: A Seven-Decade Overview," *QST*, Vol. LXIX, No. 3, March 1985, pp. 47-48. Used with permission of the American Radio Relay League.



UNITED STATES OF AMERICA

Department of Commerce and Labor

NAVIGATION SERVICE

OPERATOR'S CERTIFICATE OF SKILL IN RADIOCOMMUNICATION

This is to certify that, under the provisions of the Act of June 24, 1910,

CHARLES H. STEWART, St. David's, Pa.

has been examined in radiocommunication and has passed in:

(a) The adjustment of apparatus, correction of faults, and change from one wave-length to another;

(b) Transmission and sound-reading at a speed of not less than fifteen words a minute American Morse, twelve words Continental, five letters counting as one word.

The candidate's practical knowledge of adjustment was tested on a Stone set of apparatus.* His knowledge of other systems and of international radiotelegraphic regulations and American naval wireless regulations is shown below:

Understands United Wireless Telegraph Company's System; familiar with international radiotelegraphic regulations and American naval wireless regulations; examined and passed in both Continental and American Morse Systems.

W. S. Howard
(Signature of examining officer)
Captain, U. S. Navy.

Place Navy Yard, Philadelphia, Date August 28, 1911, 191

By direction of the Secretary of Commerce and Labor:

W. Chamberlain
Commissioner of Navigation, Washington, D. C.

I, Charles H. Stewart, do solemnly swear that I will faithfully preserve the secrecy of all messages coming to my knowledge through my employment under this certificate; that this obligation is taken freely, without mental reservation or purpose of evasion, and that I will well and faithfully discharge the duties of the office: So help me God.

Chas H Stewart
(Signature of holder.)

Date of birth July 4th, 1873 Place of birth Philada. Pa.

Sworn to and subscribed before me this 28th day of August A. D. 191/

Theodore Marks
Notary Public.

NOTARY PUBLIC
My commission expires January 15, 1913.

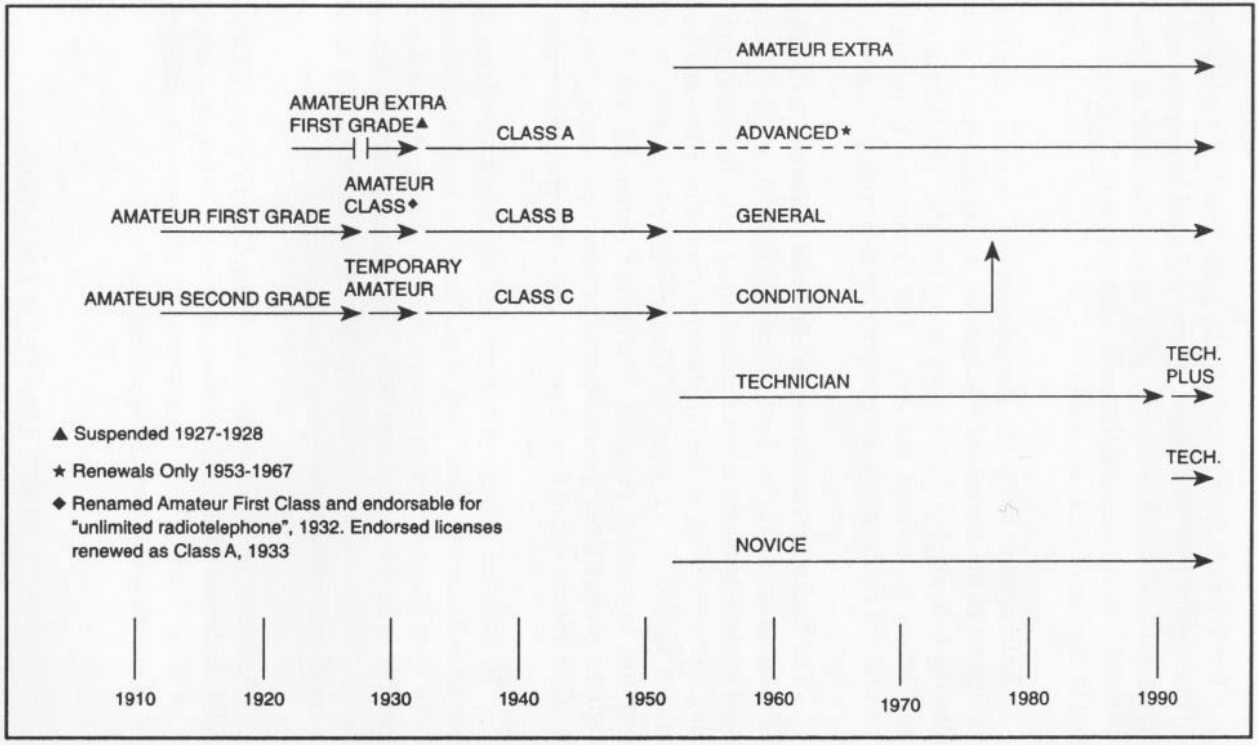
* It is not intended to limit the employment of the holder to a particular system, but merely to indicate the particular system in which he was tested for adjustment of apparatus.

This certificate is valid for two years, subject to suspension or revocation by the Secretary of Commerce and Labor for cause. It should be kept where it can be shown to officers of the customs or other officers of the Government just before the ship leaves port.

11—4797

Figure 1. "Operator's Certificate of Skill in Radiocommunication", Commerce Department, 1911. Charles H. Stewart later became a vice-president of ARRL. Size app. 10" x 20". Photo courtesy of ARRL.

U.S. Amateur Licensing, 1912-1994



U.S. did not ratify a radio convention until 1912, however, because of disputes surrounding the regulation of commercial message traffic.

The Wireless Ship Act of 1910 was the first U.S. legislation to mandate qualifications for radio operators. It required most large passenger ships, as of 1911, to carry a wireless station able to communicate at least 100 miles. Significantly, it also required that each such station be "in the charge of a person skilled in the use of such apparatus."[1]

Enforcement fell to the Department of Commerce and Labor where it was assigned to the Bureau of Navigation, whose duties at the time included monitoring U.S. shipbuilding and seagoing freight. The Bureau created a new Radio Service to enforce the Act. The Commerce Department remained responsible for licensing radio operators for two critical decades.

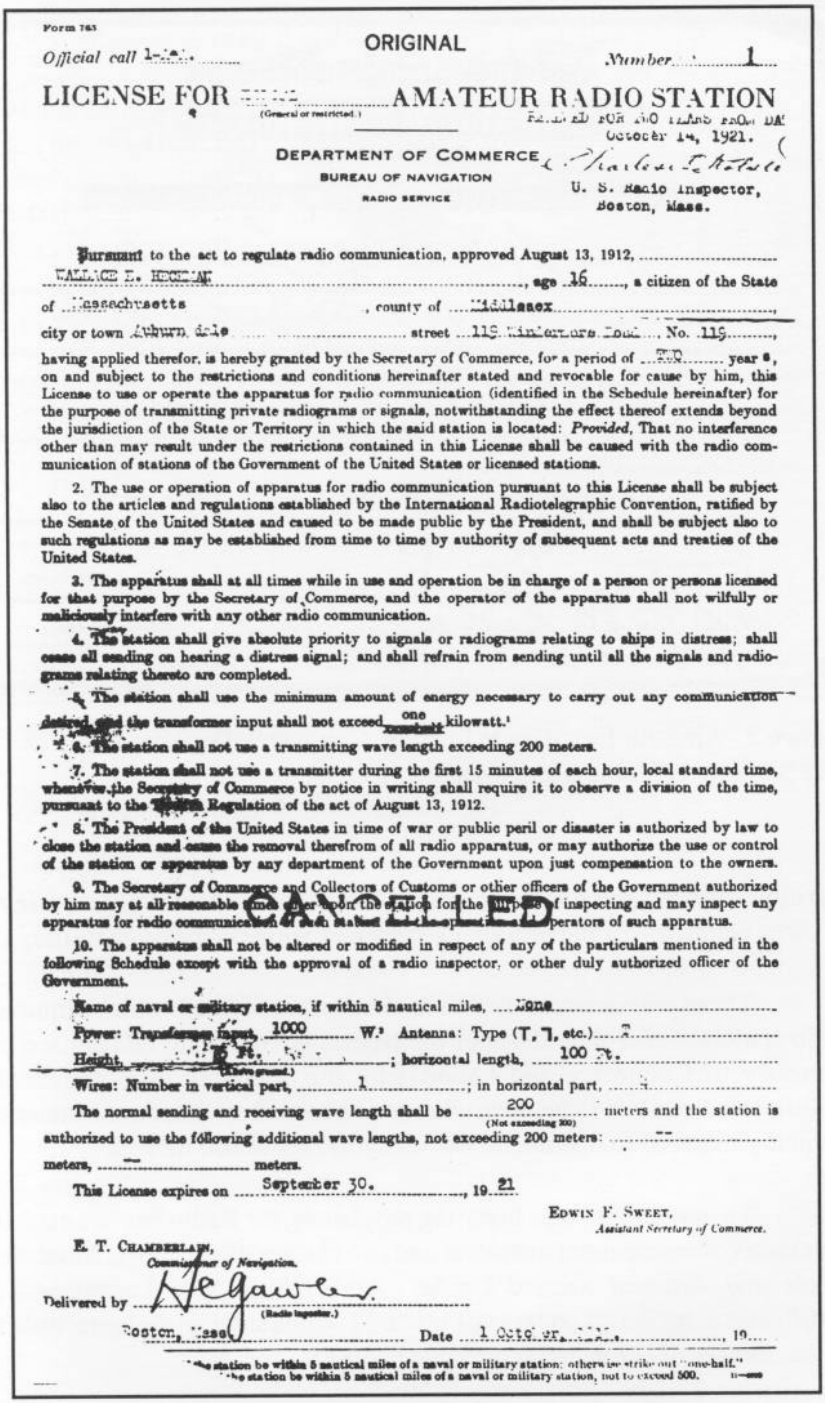
The Radio Service issued an elaborate "Operator's Certificate of Skill in Radio communication" to those found qualified to operate shipboard stations. It tested applicants on the adjustment of equipment, laws and regulations, and sending and receiving, at the applicant's choice of 15 words per minute in American Morse or 12 wpm in Continental code, or both. The Berlin Convention, in contrast, required 20 wpm in Continental code.[2] As with tests through the present date, speeds were calculated by counting five letters to the word. One minute out of five of perfect copy was required to pass.

To examine shipboard stations and operators, the Radio Service sent inspectors to Baltimore, New York, San Francisco, and New Orleans. As these locations were inconvenient to much of the population, the Service entered into agreements with the Navy and War Departments and, in Washington, the Bureau of Standards, to examine applicants under delegated authority. The Navy conducted most of the operator examinations.[3]

Amateurs were not required to obtain Certificates of Skill. According to ARRL historian Clinton B. DeSoto, however, "While it is not known how many of these [certificates] were issued to amateurs, the probability is that amateurs got the greater percentage of them."[4]

FIRST AMATEUR LICENSES

Even as the 1910 Act took effect, it was clear that the nation would not long continue without comprehensive radio regulation. Forces militating for additional laws included rapid progress in the radio art, increasing spectrum usage by amateur, commercial, and government interests, the value of radio in



Form 763

ORIGINAL

Official call 1-[illegible] *Number* 1

LICENSE FOR [illegible] AMATEUR RADIO STATION

(General or restricted.)

ISSUED FOR TWO YEARS FROM DATE
October 14, 1921.

DEPARTMENT OF COMMERCE
BUREAU OF NAVIGATION
RADIO SERVICE

U. S. Radio Inspector,
Boston, Mass.

Pursuant to the act to regulate radio communication, approved August 13, 1912, WALLACE E. HEGEMAN, age 16, a citizen of the State of Massachusetts, county of Middlesex, city or town Auburn dale street 119 Winthrop Road, No. 119, having applied therefor, is hereby granted by the Secretary of Commerce, for a period of two years, on and subject to the restrictions and conditions hereinafter stated and revocable for cause by him, this License to use or operate the apparatus for radio communication (identified in the Schedule hereinafter) for the purpose of transmitting private radiograms or signals, notwithstanding the effect thereof extends beyond the jurisdiction of the State or Territory in which the said station is located: *Provided*, That no interference other than may result under the restrictions contained in this License shall be caused with the radio communication of stations of the Government of the United States or licensed stations.

2. The use or operation of apparatus for radio communication pursuant to this License shall be subject also to the articles and regulations established by the International Radiotelegraphic Convention, ratified by the Senate of the United States and caused to be made public by the President, and shall be subject also to such regulations as may be established from time to time by authority of subsequent acts and treaties of the United States.

3. The apparatus shall at all times while in use and operation be in charge of a person or persons licensed for that purpose by the Secretary of Commerce, and the operator of the apparatus shall not wilfully or maliciously interfere with any other radio communication.

4. The station shall give absolute priority to signals or radiograms relating to ships in distress; shall cease all sending on hearing a distress signal; and shall refrain from sending until all the signals and radiograms relating thereto are completed.

5. The station shall use the minimum amount of energy necessary to carry out any communication desired, and the transformer input shall not exceed one kilowatt.[1]

6. The station shall not use a transmitting wave length exceeding 200 meters.

7. The station shall not use a transmitter during the first 15 minutes of each hour, local standard time, whenever the Secretary of Commerce by notice in writing shall require it to observe a division of the time, pursuant to the [illegible] Regulation of the act of August 13, 1912.

8. The President of the United States in time of war or public peril or disaster is authorized by law to close the station and cause the removal therefrom of all radio apparatus, or may authorize the use or control of the station or apparatus by any department of the Government upon just compensation to the owners.

9. The Secretary of Commerce and Collectors of Customs or other officers of the Government authorized by him may at all reasonable times refer upon the station for the purpose of inspecting and may inspect any apparatus for radio communication of such station and the operators of such apparatus.

10. The apparatus shall not be altered or modified in respect of any of the particulars mentioned in the following Schedule except with the approval of a radio inspector, or other duly authorized officer of the Government.

Name of naval or military station, if within 5 nautical miles, None

Power: Transformer input, 1000 W.[2] Antenna: Type (T, ┐, etc.) T

Height, 50 Ft. (Above ground.); horizontal length, 100 Ft.

Wires: Number in vertical part, 1; in horizontal part, 4

The normal sending and receiving wave length shall be 200 (Not exceeding 200) meters and the station is authorized to use the following additional wave lengths, not exceeding 200 meters: —

meters, — meters.

This License expires on September 30, 1921.

EDWIN F. SWEET,
Assistant Secretary of Commerce.

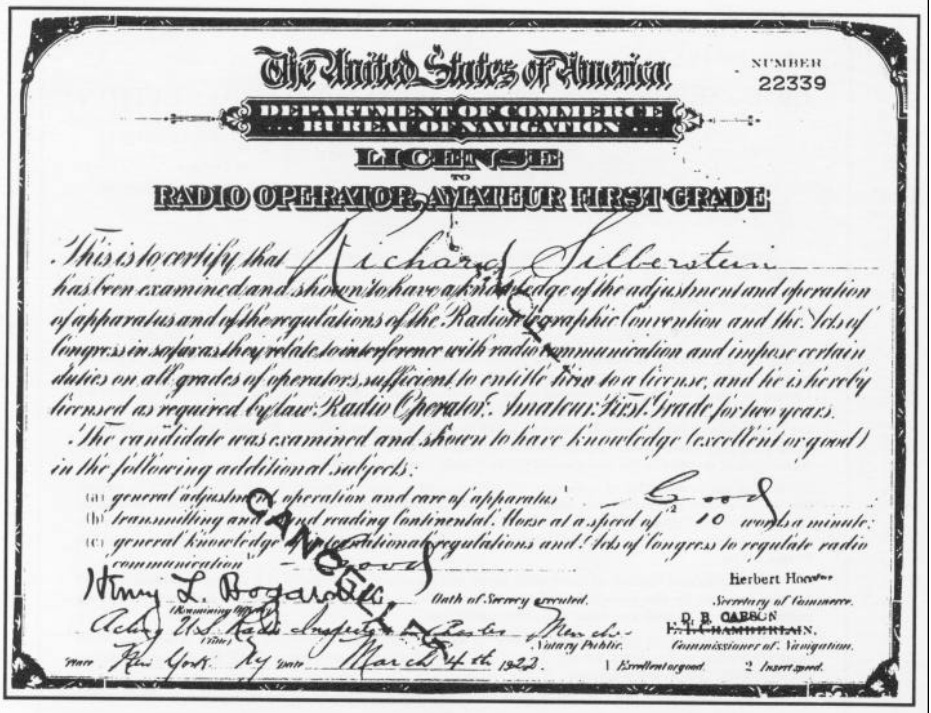
E. T. CHAMBERLAIN,
Commissioner of Navigation.

Delivered by [signature] (Radio Inspector.)

Boston, Mass. Date 1 October, 1921.

[1] "The station be within 5 nautical miles of a naval or military station: others ise strike out "one-half."
[2] The station be within 5 nautical miles of a naval or military station, not to exceed 500.

Figure 2. Amateur Station License, Commerce Department, 1919. Post-WW I License No. 1, Call 1AA. Size 8 1/2" x 14".
Photo Courtesy of ARRL



The United States of America

NUMBER 22339

DEPARTMENT OF COMMERCE
BUREAU OF NAVIGATION

LICENSE
TO
RADIO OPERATOR, AMATEUR FIRST GRADE

This is to certify that Richard Silberstein has been examined and shown to have a knowledge of the adjustment and operation of apparatus and of the regulations of the Radiotelegraphic Convention and the Acts of Congress in so far as they relate to interference with radio communication and impose certain duties on all grades of operators, sufficient to entitle him to a license, and he is hereby licensed as required by law: Radio Operator, Amateur First Grade for two years.

The candidate was examined and shown to have knowledge (excellent or good) in the following additional subjects:

(a) general adjustment, operation and care of apparatus Good
(b) transmitting and sending and reading Continental Morse at a speed of 10 words a minute;
(c) general knowledge of the additional regulations and Acts of Congress to regulate radio communication Good

Henry L. Bogardus
(Examining Officer)
Acting U.S. Radio Inspector in Charge
(Title)

Oath of Secrecy executed.
Notary Public.

Herbert Hoover
Secretary of Commerce.
D. B. CARSON
Commissioner of Navigation.

Place New York By Date March 4th 1922.

1 Excellent or good. 2 Insert speed.

Figure 3. Amateur First-Grade License, Commerce Department, 1922. Size 9 3/4" x 12", blue background.

Photo courtesy of Richard Silberstein, W0YBF

maritime disasters, such as the sinking of the Titanic in April 1912, and demands of other countries for the orderly exchange of wireless message traffic.

These pressures resulted in the Radio Act of 1912, which required that radio stations, other than those of the federal government, be licensed by the Secretary of Commerce and Labor (later the Secretary of Commerce). In addition, stations had to be in the charge of licensed operators. Amateurs were normally required to operate on wavelengths below 200 meters.[5]

To implement these licensing provisions, the Radio Service established six classes of commercial operators and two classes of amateurs, Amateur First Grade and Amateur Second Grade. After World War I amateur license certificates were issued on large (9 1/2" x 12") blue stock in diploma-style form, in the manner of commercial operator licenses.

Applicants for Amateur First Grade had to pass a written test on the adjustment of equipment and on applicable laws and regulations.[6] The first ARRL Handbook in 1926 called the examination "not difficult," requiring the

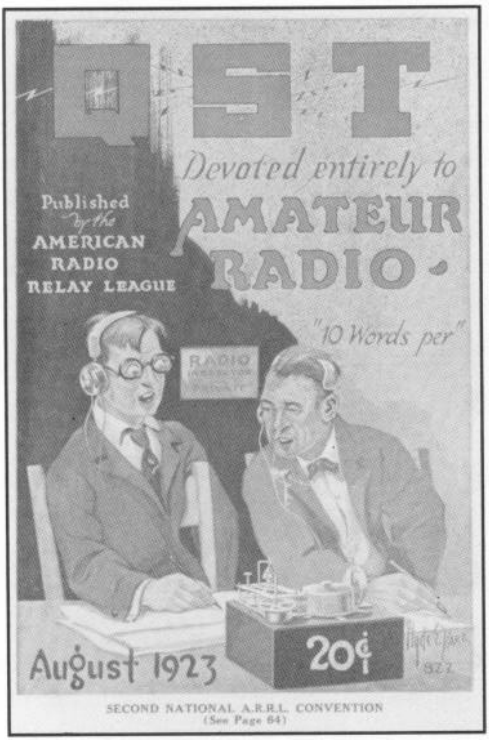


Figure 4. Commerce Department Radio Inspector administers the 10-wpm amateur code test using Omnigraph machine. *QST*, Vol. III, No. 1, August, 1923.
Photo: Author's collection.

applicant "to tell what apparatus he expects to use, to draw a simple diagram of connections, and to explain the operation."[7] The examining officer noted on the license whether the applicant's knowledge in these areas was "good" or "excellent" (they were tough graders, as most licenses I have seen only state "good"). At some point in the 1920s, the test was standardized at ten essay-type questions. The back of the license included a notarized oath by the applicant to maintain the secrecy of messages and space for the operator to log his or her "service record" at different stations.

The Continental code test, originally 5 wpm, was raised to 10 wpm by 1919.[8] It was to be "conducted by means of the Omnigraph or other automatic instrument wherever possible."[9] *QST*'s front cover for April, 1923, a drawing of a Radio Inspector administering the test, suggests that Omnigraphs (clockwork mechanical code generators) were often used.

Examinations for Amateur First Grade were regularly held at Radio Service headquarters in Washington, at nine field offices, and at military posts in Alaska and Hawaii.[10] Prospective hams unable to travel to a test site could seek an Amateur Second Grade license. Applicants had to satisfy the nearest Radio Inspector that they could not appear for an exam but were nevertheless qualified to operate a station.[11] They took "a brief examination by mail" and had two licensees certify to their ability to copy code at 10 wpm.[12]

The two grades conveyed identical privileges, the right to operate an amateur station. The type of station license held determined the authorized operating frequencies. The Radio Service issued station licenses, initially General, Restricted or Special, as separate 8 1/2" x 12" certificates. The specific privileges authorized by station licenses changed often over the years and are beyond the scope of this article.

Many hams, used to operating without government regulation, did not quickly accept the new licensing requirements. DeSoto stated, nearly a decade after the 1912 Act,

> The 200-meter restriction, the power restriction, even the licensing requirement, existed to a considerable extent in name only.

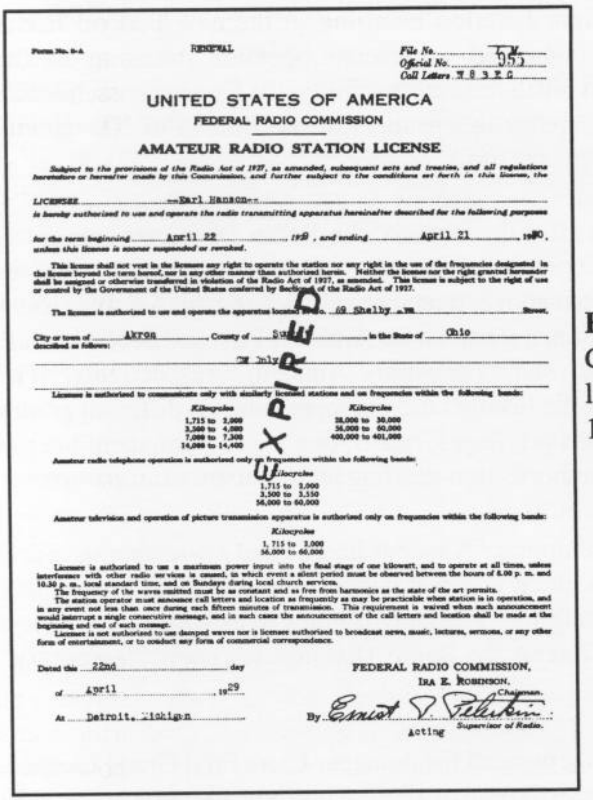
However, following the threat of onerous additional government regulation in 1921, compliance improved.[13]

THE PINK TICKET

The Radio Act of 1912 did not entirely restrict amateur operation to the legendary "200 meters and down." Hams could use longer wavelengths, but only "by special authority of the Secretary of Commerce contained in the license of the station." The potential for interference with government and commercial stations was a prime consideration in the exercising of this authority. At first the Radio Service issued "Special" amateur station licenses (with distinctive "Z" calls, as in "2ZRM"), allowing such operation to hams with at least two years of experience, if "some substantial benefit to the art or to commerce apart from individual amusement seems probable."[14]

Beginning in 1923, the Radio Service restricted Special amateur station licenses, which then authorized cw operation at 150-200 meters, to holders of a new class of operator license, the Amateur Extra First Grade. This title matched that of the highest commercial license, the Commercial Extra First Grade. Available only to amateurs with two years of experience, the new license required an advanced, ten-question written examination and a code test at 20 wpm, the speed then required of Commercial First Class operators. The large diploma-style licenses were issued on pink stock![15] This Amateur Extra First Grade license marked the first use of extra privileges as incentives for hams to upgrade their skills.

While the new license achieved some early popularity, the attraction of 150-meter privileges rapidly declined as amateur interests shifted to the exciting propagation characteristics of the short waves. In 1927 the Commerce Department reported that "nearly all of the amateur stations are now operating



Form No. 9-A RENEWAL File No. [illegible] 1953
Official No. [illegible]
Call Letters W 8 S X C

UNITED STATES OF AMERICA
FEDERAL RADIO COMMISSION

AMATEUR RADIO STATION LICENSE

Subject to the provisions of the Radio Act of 1927, as amended, subsequent acts and treaties, and all regulations heretofore or hereafter made by this Commission, and further subject to the conditions set forth in this license, the

LICENSEE --Earl Hanson--

is hereby authorized to use and operate the radio transmitting apparatus hereinafter described for the following purposes

for the term beginning April 22, 1929, and ending April 21, 1930, unless this license is sooner suspended or revoked.

This license shall not vest in the licensee any right to operate the station nor any right in the use of the frequencies designated in the license beyond the term hereof, nor in any other manner than authorized herein. Neither the license nor the right granted hereunder shall be assigned or otherwise transferred in violation of the Radio Act of 1927, as amended. This license is subject to the right of use or control by the Government of the United States conferred by Section [illegible] of the Radio Act of 1927.

The licensee is authorized to use and operate the apparatus located at 69 Shelby ... Street,

City or town of Akron, County of Summit, in the State of Ohio described as follows:

CW only

Licensee is authorized to communicate only with similarly licensed stations and on frequencies within the following bands:

Kilocycles	Kilocycles
1,715 to 2,000	30,000 to 40,000
3,500 to 4,000	56,000 to 60,000
7,000 to 7,300	400,000 to 401,000
14,000 to 14,400	

Amateur radio telephone operation is authorized only on frequencies within the following bands:

Kilocycles
1,715 to 2,000
3,500 to 3,550
56,000 to 60,000

Amateur television and operation of picture transmission apparatus is authorized only on frequencies within the following bands:

Kilocycles
1,715 to 2,000
56,000 to 60,000

Licensee is authorized to use a maximum power input into the final stage of one kilowatt, and to operate at all times, unless interference with other radio services is caused, in which event a silent period must be observed between the hours of 6.00 p. m. and 10.30 p. m., local standard time, and on Sundays during local church services.
The frequency of the waves emitted must be as constant and as free from harmonics as the state of the art permits.
The station operator must announce call letters and location as frequently as may be practicable when station is in operation, and in any event not less than once during each fifteen minutes of transmission. This requirement is waived when such announcement would interrupt a single consecutive message, and in such cases the announcement of the call letters and location shall be made at the beginning and end of such message.
Licensee is not authorized to use damped waves nor is licensee authorized to broadcast news, music, lectures, sermons, or any other form of entertainment, or to conduct any form of commercial correspondence.

Dated this 22nd day of April, 1929
At Detroit, Michigan

FEDERAL RADIO COMMISSION,
IRA E. ROBINSON, Chairman.
By [signature] Acting Supervisor of Radio.

EXPIRED

Figure 5. Federal Radio Commission amateur station license, 1929. Size 8" x 10 1/2".
Photo: Author's collection

on wave lengths of 80 meters and below."[16] The Amateur Extra First Grade attracted very few applicants that year and was temporarily discontinued in fiscal 1928.[17]

The broadcast boom of the 1920s quickly made the 1912 Act obsolete. The Bureau of Navigation reported in 1923 that

> It is becoming more difficult each year to apply the existing law of 1912 to services which not only did not exist but were not contemplated when the present law was enacted.[18]

As a stop-gap measure, Secretary of Commerce (later president) Herbert Hoover convened annual National Radio Conferences to encourage orderly spectrum usage through mutual agreement. Chaos threatened, however, when the Attorney General ruled in 1926, after an adverse court decision,[19] that the Commerce Department, which could not deny requests for broadcast licenses, had no authority to restrict stations to specific wave lengths, hours of operation, or power limits.[20] Stations could broadcast however they liked! To restore order, Congress quickly passed the Radio Act of 1927, which gave the government the needed regulatory authority to control the spectrum.[21]

The 1927 Act assigned station licensing to the new Federal Radio Commission (FRC), but continued to reserve operator licensing to the Commerce Department. To fulfill this responsibility, the Department created a new Radio Division as an agency independent of the Bureau of Navigation, reporting directly to the Secretary of Commerce.[22]

Just a few months after its creation, the Radio Division revised the operator licensing system. It reduced the number of commercial license classes from six to three, and, as noted above, it temporarily deleted the Amateur Extra First Grade license. In addition, it renamed the Amateur First and Second Grade licenses as "Amateur Class" and "Temporary Amateur," respectively. The name changes reflected that the licenses did not represent two different grades of operator qualifications and privileges; rather, one was a permanent license and the other a temporary authorization pending an in-person examination.

Initially, the new Temporary Amateur license had a one-year term and could not be renewed. The intent was that hams could no longer indefinitely avoid a government examination.[23] The lack of funds to establish enough test sites, however, eventually forced the Radio Division to renew "temporary" licenses.[24]

The Radio Division reinstated the Amateur Extra First Grade License, with its special written exam, at the end of 1928. This time, the code test was 20 wpm in plain language and 16 five-letter random groups per minute.[25] This is the only instance of the government testing hams on copying random code groups, and it is unclear why it did so.

The following year, 1929, the FRC granted phone privileges on the exciting new 20-meter band to amateurs determined by the Radio Division to be qualified for such work.[26] The Radio Division responded by endorsing Amateur Extra First Grade licenses as follows:

> The holder of this license examined and certified for unlimited radiotelephone operation under Federal Radio Commission Regulation No. 377.[27]

In 1932 Congress transferred the Radio Division and its duties to the FRC, centralizing amateur operator and station regulation in the Commission. Among the Division's final acts was the granting to those Amateur Class operators who passed a ten-question exam on phone theory the "unlimited radiotelephone" endorsement previously reserved to Amateur Extra First Grade licensees. The new test was not as comprehensive as that for the top license, and no additional code exam was required. The Radio Division also added 75 meters as a phone band reserved for holders of the endorsement.[28]

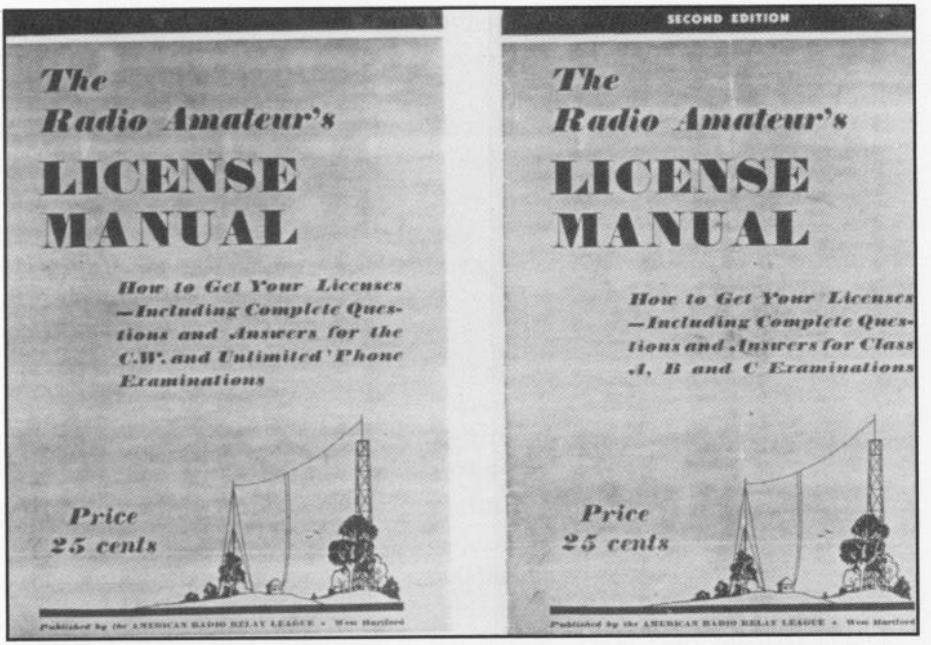


Figure 6. First ARRL License Manual, May, 1933, on the left. The 2nd Edn. on the right, Sept. 1933, reflected the June revisions of the licensing system by the FRC. Photo: Author's collection

At the end of the year, the FRC discontinued the fancy, diploma-style operator licenses for plainer, 8" x 10 1/2" forms similar to the station licenses of the time.[29] It also renamed the Amateur Class license as Amateur First Class.[30] Perhaps the latter change was initiated by former Amateur First Grade licensees who felt they had lost status by the 1927 name change to Amateur Class.

By the end of 1932, then, four types of licenses in two distinct groups were available. In the first group, the Temporary Amateur license and Amateur First Class conveyed basic privileges. In the second group, Amateur First Class was endorsed for "unlimited radiotelephone," and Amateur Extra First Grade allowed, in addition to the above, operation in the 20- and 75-meter phone bands.

THE "A-B-C" ERA

The next year, 1933, the FRC simplified the license structure and changed the class names to A, B, and C. It also began issuing combined amateur licenses (operator on one side, station on the other) on a wallet-sized (about 3" x 5") card. Amateur First Class became Class B, a change of little more than

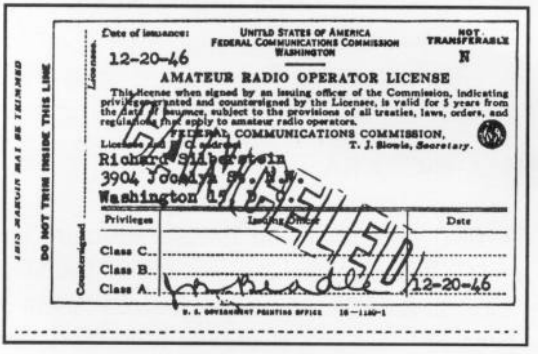
name. Class B and Class C conveyed all operating privileges except the phone bands, which were reserved to Class A licensees.

Amateur Extra First Grade and those Amateur First Class licenses that were endorsed for "unlimited radiotelephone," were merged into Class A, and, in later decades 20- and 75-meters were commonly referred to as the "Class A phone bands." The additional Class A written test was a ten-question examination on radiotelephone subjects. No code test, beyond the 10 wpm for Class B, was required.[31]

The replacement of Temporary Amateur by Class C, on the other hand, involved substantial changes. Temporary Amateurs were not grandfathered into Class C; they had to pass the written and code exams and otherwise qualify anew. License requirements were stiffened. *QST,* the official publication of the ARRL, derisively called the self-administered written exam for Temporary Amateur "the skimpiest possible test."[32] In contrast, Class C required the same ten-question essay exam as Class B, taken before a certifying witness. Where the Temporary Amateur applicant simply declared that he or she could copy code at 10 wpm, the Class C applicant was required to take a code test from a volunteer examiner, often necessitating considerable travel.

The Communications Act of 1934, still in force today, although much amended, created the Federal Communications Commission (FCC).[33] The FCC consolidated the broad spectrum powers of the FRC with the wireline communications authority previously exercised by the Interstate Commerce Commission. To date, the FCC has regulated U.S. amateur radio for 61 years. For the first 17, it continued the A-B-C licensing system begun by the FRC.

In May, 1936, the ARRL petitioned the FCC to raise the code requirement for all classes to 12.5 wpm.[34] Perry Williams, W1UED, a former ARRL Washington Area Coordinator, suggests this was instigated by ardent traffic handlers seeking to raise the level of code proficiency. The


Date of issuance: 12-20-46

UNITED STATES OF AMERICA
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON

NOT TRANSFERABLE
N

AMATEUR RADIO OPERATOR LICENSE

This license when signed by an issuing officer of the Commission, indicating privileges granted and countersigned by the Licensee, is valid for 5 years from the date of issuance, subject to the provisions of all treaties, laws, orders, and regulations that apply to amateur radio operators.

FEDERAL COMMUNICATIONS COMMISSION,
T. J. Slowie, *Secretary.*

Licensed and Graduated
Richard Silberstein
3904 Jocelyn St. N.W.
Washington 15, D. C.

Privileges | Issuing Officer | Date
Class C.
Class B.
Class A. 12-20-46

Licensee.
Countersigned
DO NOT TRIM INSIDE THIS LINE
1913 MANUAL MAY BE TRIMMED

U. S. GOVERNMENT PRINTING OFFICE 16—1180-1

Figure 7. FCC Class A amateur license, 1946. Station license on the reverse. Size 2 1/2" x 4" (trimmed) card stock.
Photo courtesy of R. Silberstein, W0BYF

Commission found 12.5 wpm "messy to grade" and so in June rounded up to the 13 wpm standard that has continued through to today's General and Advanced licensees.[35] This was a significant action, given the common complaint of a learning plateau at 10-12 wpm that must be overcome to pass the test.

The Commission changed the written examinations in 1940. The old ten-question essay tests "required an amateur to write more or less a book in reply."[36] Moreover, the grading of such exams was slow and somewhat subjective. These were replaced with a fifty-question test for Class B and C and an additional forty-question test for Class A. Some of the questions required applicants to draw portions of circuit diagrams (these were eliminated in 1960[37]). Most questions, however, were multiple choice. The new tests could be graded quickly and objectively, and allowed testing on more topics.

To promote the use of the ultra-high frequencies the ARRL petitioned the FCC in 1946 for a code-free Class D license. The proposed license would allow operation above 200 MHz and require only the Class B/C written examination.[38] The League withdrew its petition a few months later, however, with amateur opinion "gradually crystallizing" against the concept.[39]

The Administrative Procedure Act of 1946 required the FCC and other federal agencies to publish proposed rules and consider public comments before adopting regulations. As a result, much more detailed published records are available for subsequent rule-making proceedings than for the earlier ones.

GENERALS AND OTHERS

In 1948 the ARRL asked the FCC to expand the Class A phone bands, establish a 16-wpm Class A code test, and bar new licensees from phone operation below 30 MHz during their first year on the air.[40] The Commission responded in 1949 by proposing a major overhaul of the licensing system. This included renaming Class A, B and C licenses with the more descriptive terms Advanced, General, and Conditional, respectively. The FCC also proposed three new license grades: Amateur Extra (named "for extra qualifications and extra privileges") at the top, and Novice and Technician at the bottom.[41]

The Commission also proposed closing the Advanced class to new applicants and downgrading existing licensees to General upon license renewal; the 20- and 75-meter phone privileges would be reserved to Amateur Extras. The new top license would require a code test at 20 wpm and a written examination more comprehensive than that previously used for Class A.

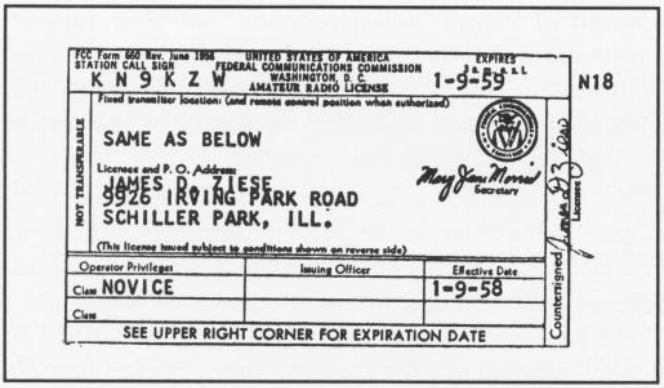

FCC Form 660 Rev. June 1956 UNITED STATES OF AMERICA EXPIRES
STATION CALL SIGN FEDERAL COMMUNICATIONS COMMISSION 3 a.m. 1-9-59 S.T.
K N 9 K Z W WASHINGTON, D. C. N18
AMATEUR RADIO LICENSE
Fixed transmitter location: (and remote control position when authorized)
NOT TRANSFERABLE
SAME AS BELOW
Licensee and P. O. Address:
JAMES D. ZIESE
9926 IRVING PARK ROAD
SCHILLER PARK, ILL.
(This license issued subject to conditions shown on reverse side)
Mary Jane Morrel Secretary
Countersigned June 23 1958 Licensee
Operator Privileges | Issuing Officer | Effective Date
Class NOVICE | | 1-9-58
Class | |
SEE UPPER RIGHT CORNER FOR EXPIRATION DATE

Figure 8. FCC Novice License, 1958. Size 1 1/2" x 4 1/4", trimmed. Photo courtesy of James Ziese, W0PWS

QST later reported that these proposals caused greater consternation among amateurs than even the incentive licensing rule making of the 1960s.[42] The League and others strongly objected to the perceived unfairness of Advanced licensees losing phone privileges, despite having earned them by passing a special exam.[43] Adopting new rules in 1951, the FCC met this concern with a grandfathering provision. Existing Advanced class hams could renew their licenses and share the restricted phone bands with Amateur Extras. After 1952, the class would be closed to new applicants.[44]

This change did not satisfy the ARRL, which reasoned that Generals and Conditionals desiring access to popular phone bands should not have to pass a 20-wpm code test and a written exam on subjects unrelated to radiotelephone operation.[45] The attraction of 20 and 75 meters must be viewed bearing in mind that the (arguably) less desirable 10- and 160-meter phone bands were the only ones available to holders of the lower classes of tickets. The 15-meter band did not yet exist, and phone operation was not allowed on 40 meters.

The FCC responded with a surprising reversal of position. Rather than either reserving privileges only for Amateur Extras and holdover Class A licensees (its prior proposal) or allowing new Advanced licensees to earn them (ARRL's position), in 1953 it opened the long-restricted 20- and 75-meter phone bands to the large number of Conditionals and Generals.[46] This action left four classes of licensees — Conditional, General, Advanced, and Amateur Extra — with identical privileges!

The General/Conditional/Technician written test was revised to include more questions on phone operation.[47] The Commission opened the Amateur Extra Class in 1952 and expressed the intent to reserve unspecified

privileges to the class in the future.[48] Although the new top license granted no special rights, as a token reward to those who passed the exam the FCC field offices issued, upon request, a 7" x 9" (peculiarly hard to frame) diploma-style form in addition to the usual wallet-sized license. This unusual certificate, which stated neither call letters nor expiration date, was purely ceremonial, as it stated that it was only valid to the extent the holder possessed a valid license of the regular form. Additionally, Amateur Extras who had been licensed for 25 years could also request "preferred" call signs.

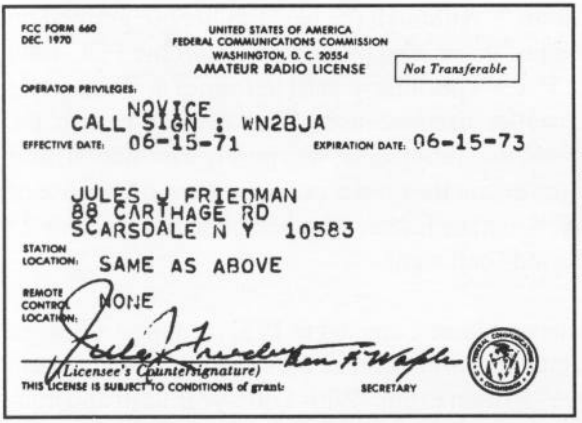
The Novice and Technician classes, created in 1951, required a 5-wpm code test. The Novice license, intended to encourage the entry of youth into ham radio, had an "extremely simple" written exam. With a one-year term and non-renewable at first, it allowed only crystal-controlled operation with 75 watts maximum input power. Operating privileges included frequencies on 11 and 80 meters, and cw and phone from 145 to 147 MHz. The Technician license, intended to stimulate experimentation at VHF and above, required the Conditional/General written test. It granted all privileges above 220 MHz.[49] Overall, Novice and Technician privileges have greatly increased over the past four decades.

At first, Novice and Technician exams were given at FCC offices or, if the applicant lived more than 125 miles from an office, they were obtained by mail and given by a volunteer examiner with at least a General license. The same procedure was followed for granting the Conditional license. After 1954, however, they became available by mail to all applicants, regardless of location of residence.

INCENTIVE LICENSING

Thirty years after the time, hams of the 1990s may find it difficult to understand the emotions aroused by the "incentive licensing" rule making of the 1960s. Strong feelings arose because the proceeding addressed basic questions about fairness to existing licensees, the proper role of government regulation, and the future of amateur radio.

An editorial in the February, 1963 issue of *QST* started the controversy. Ten years after the 20- and 75-meter phone bands were opened to General and Conditionals, it suggested that a return to restricted phone segments would improve amateur proficiency and operations.[50] Shortly afterward, the ARRL petitioned to reopen the Advanced Class to new applicants and to restrict the 15-, 20-, 40- and 75-meter phone bands to Advanced and Amateur Extra licensees, leaving phone bands for the lower classes at 10 and 160 meters, as before 1953.[51]


FCC FORM 660
DEC. 1970

UNITED STATES OF AMERICA
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON, D. C. 20554
AMATEUR RADIO LICENSE

Not Transferable

OPERATOR PRIVILEGES: NOVICE

CALL SIGN : WN2BJA

EFFECTIVE DATE: 06-15-71 EXPIRATION DATE: 06-15-73

JULES J FRIEDMAN
88 CARTHAGE RD
SCARSDALE N Y 10583

STATION LOCATION: SAME AS ABOVE

REMOTE CONTROL LOCATION: NONE

(Licensee's Counterignature)

THIS LICENSE IS SUBJECT TO CONDITIONS of grant: SECRETARY

Figure 9. FCC Novice License, 1971. Size 2 3/4" x 3 3/4", folded.
Photo: Author's collection

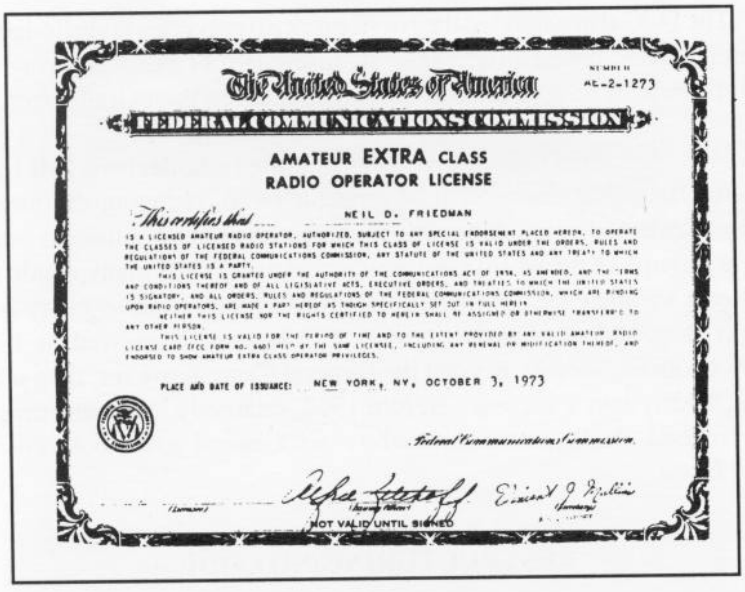
The League received about 15,000 comments from its members on incentive licensing. These divided evenly on the issue.[52] Supporters and opponents cited many arguments, but the positions may be capsulized as follows:

Those against incentive licensing felt that the proper goal of government testing was to ensure that licensees operate safely, within the regulations, and without interfering with others. They also protested the unfairness of banishing Generals and Conditionals from bands that these classes had used for years.

Those in favor argued that offering special privileges as inducements to improve skills would upgrade the skills of the amateur corps and was a legitimate use of regulatory power. They noted that grandfathering of existing Generals and Conditionals, the bulk of the amateur service, would be self-defeating, as those licensees would have no incentive to increase skills.

Of the non-ARRL ham magazines, *CQ* generally supported the principle of incentive licensing but differed as to details.[53] *73* opposed the ARRL proposal and the first FCC response, but approved the final implementation.[54]

Responding to the ARRL's petition (and ten others), the FCC issued its proposal in 1965. It planned to abolish the Advanced Class, downgrading its licensees to General. As the scope of the General examination increased in 1951 to include phone topics previously reserved for Advanced, the Commission saw little difference between the classes. A new license, Amateur First Class, would become a stepping stone between General and Amateur Extra. It would require a written exam of intermediate difficulty and a 16-wpm code test. Some band segments would be reserved for Amateur First Class and Amateur Extra licensees and others only for Amateur Extras. The FCC also proposed assigning



The United States of America

NUMBER AE-2-1273

FEDERAL COMMUNICATIONS COMMISSION

AMATEUR EXTRA CLASS
RADIO OPERATOR LICENSE

This certifies that NEIL D. FRIEDMAN

IS A LICENSED AMATEUR RADIO OPERATOR, AUTHORIZED, SUBJECT TO ANY SPECIAL ENDORSEMENT PLACED HEREON, TO OPERATE THE CLASSES OF LICENSED RADIO STATIONS FOR WHICH THIS CLASS OF LICENSE IS VALID UNDER THE ORDERS, RULES AND REGULATIONS OF THE FEDERAL COMMUNICATIONS COMMISSION, ANY STATUTE OF THE UNITED STATES AND ANY TREATY TO WHICH THE UNITED STATES IS A PARTY.

THIS LICENSE IS GRANTED UNDER THE AUTHORITY OF THE COMMUNICATIONS ACT OF 1934, AS AMENDED, AND THE TERMS AND CONDITIONS THEREOF AND OF ALL LEGISLATIVE ACTS, EXECUTIVE ORDERS, AND TREATIES TO WHICH THE UNITED STATES IS SIGNATORY, AND ALL ORDERS, RULES AND REGULATIONS OF THE FEDERAL COMMUNICATIONS COMMISSION, WHICH ARE BINDING UPON RADIO OPERATORS, ARE MADE A PART HEREOF AS THOUGH SPECIFICALLY SET OUT IN FULL HEREIN.

NEITHER THIS LICENSE NOR THE RIGHTS CERTIFIED TO HEREIN SHALL BE ASSIGNED OR OTHERWISE TRANSFERRED TO ANY OTHER PERSON.

THIS LICENSE IS VALID FOR THE PERIOD OF TIME AND TO THE EXTENT PROVIDED BY ANY VALID AMATEUR RADIO LICENSE CARD (FCC FORM 610) HELD BY THE SAME LICENSEE, INCLUDING ANY RENEWAL OR MODIFICATION THEREOF, AND ENDORSED TO SHOW AMATEUR EXTRA CLASS OPERATOR PRIVILEGES.

PLACE AND DATE OF ISSUANCE: NEW YORK, NY, OCTOBER 3, 1973

Federal Communications Commission

(Secretary) (Chairman)

NOT VALID UNTIL SIGNED

Figure 10. FCC Amateur Extra License, 1973. Diploma-style form issued upon request of licensee. 7" x 9".
Photo: Author's collection

calls with prefixes indicative of the class of license held. Technicians, for example, would get calls beginning with WT or WU.[55]

The ARRL responded by requesting that Advanced licensees be grandfathered into the new Amateur First Class without requiring the 16-wpm code test, rather than downgraded to General. It argued that Advanced hams deserved more privileges than Generals and Conditionals because they had taken pains to reach the top of the earlier (A-B-C) incentive licensing system. The League asked that Amateur Extra First Grade licensees of the Commerce Department era, downgraded to easier-to-attain Class A after 1932, be grandfathered into the Amateur Extra Class. It requested that, if new prefixes were assigned, all hams should be allowed to retain their existing call suffixes.[56]

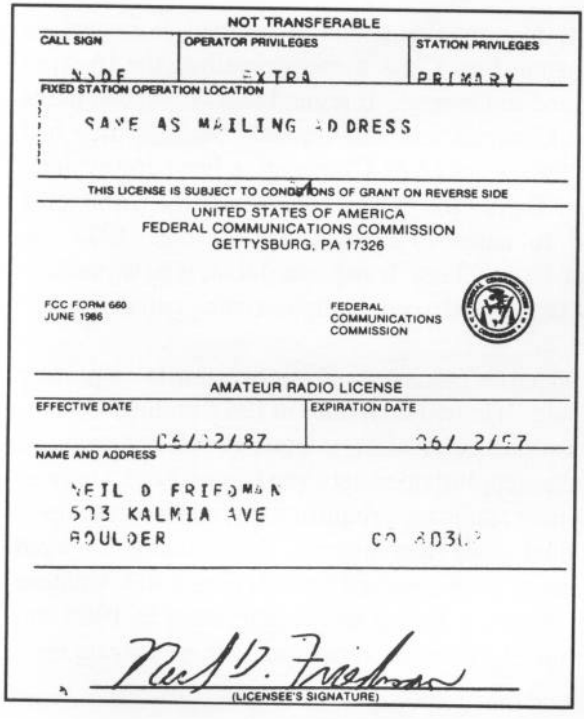
The FCC received 1,700 public comments, about two-thirds supporting the principle of incentive licensing. It issued final rules in 1967, ending the five-year controversy. The Commission abandoned its Amateur First Class proposal and made the Advanced Class the stepping stone between General and Amateur Extra. It opened Advanced to new applicants, requiring an intermediate-level written exam and no additional code test beyond the existing 13-wpm requirement. Some band segments were reserved for Advanced and Amateur Extra licensees and others for Amateur Extras alone, beginning in 1968 and 1969.[57] Generals and Conditionals, however, remained able to operate on a portion of every phone band.

The FCC also extended the Novice term to two years and eliminated the two-meter Novice phone privileges. It rescinded its call sign proposal and ignored the request to upgrade former Amateur Extra First Grade licensees.

Was the return to incentive licensing the right decision? It has been blamed for flattening the growth of amateur radio, reducing the number of equipment dealers, driving American manufacturers out of business, and even letting Japan capture the world electronics markets. While many would ascribe these events to other causes, incentive licensing did deprive many hams of privileges they had previously enjoyed. If success is viewed as inducing licensees to obtain licenses beyond the General Class, however, then incentive licensing clearly was a success. Before 1962, relatively few hams progressed beyond General. Today, most hams who reach General go on to Advanced and Amateur Extra.

RESTRUCTURING/NO CODE

The Commission must have liked the results of its incentive licensing handiwork, for just a few years later, in 1974, it proposed what must be the ultimate in an incentive-based system. "Restructuring," as it was known, contemplated seven distinct license classes, each with its own examination and special privileges.[58]


NOT TRANSFERABLE

CALL SIGN	OPERATOR PRIVILEGES	STATION PRIVILEGES
N>DE	EXTRA	PRIMARY

FIXED STATION OPERATION LOCATION

SAME AS MAILING ADDRESS

THIS LICENSE IS SUBJECT TO CONDITIONS OF GRANT ON REVERSE SIDE

UNITED STATES OF AMERICA
FEDERAL COMMUNICATIONS COMMISSION
GETTYSBURG, PA 17326

FCC FORM 660
JUNE 1986

FEDERAL COMMUNICATIONS COMMISSION

AMATEUR RADIO LICENSE

EFFECTIVE DATE	EXPIRATION DATE
06/12/87	06/12/97

NAME AND ADDRESS

NEIL D FRIEDMAN
503 KALMIA AVE
BOULDER CO 8030>

Neil D. Friedman
(LICENSEE'S SIGNATURE)

Figure 11. FCC Amateur Extra License, front and back, 1987. Pattern of yellow FCC seals on a white background. 2 1/2" x 3 3/4", folded.
Photo: Author's collection

The proposal planned two license "ladders": one with HF privileges (Novice, General, and Advanced) and one with VHF/UHF privileges (Communicator, Technician, and Experimenter). At the top, the Extra Class (no "Amateur") would convey all privileges. An individual could hold one license in each chain. Extra would require a code test at 20 wpm; Advanced and General at 13; and Novice, Experimenter, and Technician at 5. Grandfathering provisions were generous.

The most controversial part of the plan involved the entry-level Communicator license. Requiring a simple written examination and no code test, it would convey broad privileges above 144 MHz. Most of the 56,000 respondents to an ARRL membership survey objected to the no-code plan.[59] The League countered with its own "slow code" proposal; a Basic Amateur Class would be added below Novice on the existing license scheme. The new class would allow privileges at 144 and 220 MHz, share an expanded Novice written test, and require that applicants identify letters in code (e.g.,dit-dah equals A) at no specific speed.[60]

As an interim measure, in 1976 the FCC eliminated much of its long-standing volunteer examiner program (often derisively referred to as "mail-order licensing") because of abuse. Ninety percent of the Technicians and Conditionals who were called to retake their tests before Commission personnel either failed or did not appear. Henceforth, Technician applicants were examined by FCC personnel. No new Conditional licenses were issued, with existing licensees grandfathered to General. The FCC also granted Novice privileges to Technicians and eased Novice transmitting limitations.[61]

The Commission stopped requiring a code sending test for any class of license in 1977. It found that over 99 per cent of applicants passing the code receiving test also passed the sending test.[62] Perhaps even more significantly, without the sending test amateur exams could be given by clerical personnel instead of the higher paid field engineers.

In 1979, the FCC announced it would take no action on a code-free license, but would revisit the issue in the future. Most of the 4,000 public comments asserted that the proposed privileges were too generous, given the Communicator license's limited requirements, but the Commission disagreed and suggested that public sentiment might have changed since it proposed the plan in 1975. It also stated that the dual-ladder licensing scheme would not be pursued due to workload problems. The Novice license was made renewable and given the same five-year term as other classes.[63]

Nearly a half-century after the government began using volunteer amateurs to administer code and written exams, the FCC's General Counsel, curiously enough, declared in 1979 that the acceptance of such services without

specific statutory authorization violated federal law. This opinion threatened the continuation of the Novice license program, which still depended upon volunteer examiners.[64]

The ARRL actively pursued corrective legislation, first as part of an ongoing Congressional "rewrite" of the Communications Act of 1934 and, when the rewrite died, as a separate amendment to the Act. The "[Barry] Goldwater Amateur Radio Legislation," enacted in 1982, authorized the FCC to accept voluntary services from licensed amateurs.[65] A later amendment, avidly sought by the ARRL, authorized examiners to charge limited fees to recover their expenses.

The Commission seized upon its new authority to ease the burden of amateur licensing on its resources. In 1983 it began selecting organizations, including the ARRL, to coordinate examinations above Novice, to be given by groups of three hams accredited as volunteer examiners.[66]

The volunteer examiners began the testing in 1984. The new system conserved FCC resources and expanded testing opportunities for applicants. In addition, it opened the process of question-pool formation to public scrutiny. The system worked so well that in 1993 the FCC made Novice testing a responsibility of the volunteer coordinators.

The volunteer examining system resulted in other changes to the licensing process. Applicants passing either the written or the code test for a grade of license would receive credit for it if the other portion of the examination was passed within a year. Applicants could pass the code test with either a minute of solid copy or by answering questions on the content of the message received.

NO CODE AGAIN...AND AGAIN

True to its word, the FCC revisited the issue of a code-free license in 1983. Contending that such a license would bring more computer-oriented youth into amateur radio, it proposed two alternatives. In one, a Technician license with no code test would allow operation above 30 MHz. (The 1979 World Administrative Radio Conference had lowered the frequency below which international law required knowledge of the code, from 144 to 30 MHz.) In the other, a new code-free Experimenter Class, patterned after the Canadian Digital Amateur Class, would require an examination emphasizing digital modes and would allow VHF/UHF privileges.[67]

Of the 5,000 comments received by the Commission, opponents of a code-free license outnumbered supporters by 20 to 1![68] The ARRL argued that

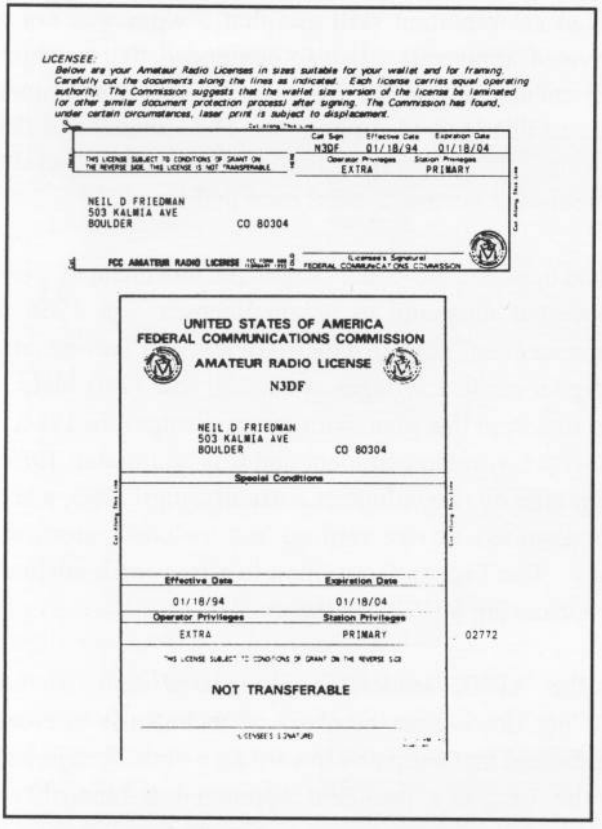
knowledge of code remained an important skill and that 5 wpm was not a significant barrier to motivated applicants. It also contended that a major change in licensing would unduly burden the fledgling volunteer examiner testing system.[69] Acceding to this lack of support, the FCC abandoned the proposal at the end of 1983. *QST*, paraphrasing Commission officials, pronounced the issue of a code-free license "buried once and for all."[70]

While the ARRL had opposed "no-code," it realized that changes were needed to entice more potential amateurs to obtain licenses. In 1985 it petitioned for a "Novice enhancement" plan, in which Novices and Technicians would receive voice and digital mode privileges at 28, 220 and 1240 MHz.[71] The Commission proposed to accept this plan, with minor changes, in 1986.[72] Novice Enhancement met with favorable comment and was adopted in 1987. Novice tests were given thereafter by two volunteer amateurs (until 1993, when the volunteer coordinators assumed Novice testing) and included questions covering the new privileges. The Technician written test mas made distinct from the General exam, emphasizing VHF/UHF theory.[73]

Soon afterward, the ARRL leadership recognized that Novice enhancement alone would not draw large numbers of technically-oriented newcomers into amateur radio and that antipathy toward a no-code license was easing. In early 1989, the League's president appointed a blue-ribbon committee to make recommendations with regard to a code-free license. It included representatives of ARRL, industry, and the general ham community. Consultants to the committee included the presidents of the Canadian Radio Relay League and the Quarter Century Wireless Association.[74]

The committee recommended that a code-free Technician license convey all privileges above 30 MHz, excepting 144.9 to 145.1 MHz). Upon passing a 5-wpm code test, licensees could upgrade to Technician Plus and receive all of the prior Novice/Technician privileges. Existing Technicians would be grandfathered into the Tech Plus class.[75] The ARRL petitioned for a code-free license later in the year, but called the class "Communicator," with privileges only above 220 MHz.[76]

Responding to the ARRL and eleven other petitioners, the FCC proposed a code-free Communicator license with privileges above 222 MHz. The written exam would come from the Novice and Technician question pools, with some added topics. An upgrade to General would require the General written test and a 13-wpm code exam. No new Novice and Technician licenses would be issued, but existing licensees could renew indefinitely.[77]



LICENSEE:
Below are your Amateur Radio Licenses in sizes suitable for your wallet and for framing. Carefully cut the documents along the lines as indicated. Each license carries equal operating authority. The Commission suggests that the wallet size version of the license be laminated for other similar document protection process) after signing. The Commission has found, under certain circumstances, laser print is subject to displacement.

Call Sign N3DF | Effective Date 01/18/94 | Expiration Date 01/18/04
THIS LICENSE SUBJECT TO CONDITIONS OF GRANT ON THE REVERSE SIDE. THIS LICENSE IS NOT TRANSFERABLE
Operator Privileges: EXTRA | Station Privileges: PRIMARY

NEIL D FRIEDMAN
503 KALMIA AVE
BOULDER CO 80304

FCC AMATEUR RADIO LICENSE — Licensee's Signature — FEDERAL COMMUNICATIONS COMMISSION

UNITED STATES OF AMERICA
FEDERAL COMMUNICATIONS COMMISSION
AMATEUR RADIO LICENSE
N3DF

NEIL D FRIEDMAN
503 KALMIA AVE
BOULDER CO 80304

Special Conditions

Effective Date	Expiration Date
01/18/94	01/18/04
Operator Privileges	Station Privileges
EXTRA	PRIMARY

02772

THIS LICENSE SUBJECT TO CONDITIONS OF GRANT ON THE REVERSE SIDE

NOT TRANSFERABLE

LICENSEE'S SIGNATURE

Figure 12. FCC Amateur Extra License, 1994. Laser-printed wallet and framable forms, uncut. 2 1/4" x 3 1/2", trimmed and folded, and 5" x 7", trimmed.
Photo: Author's collection

The ARRL strongly objected to the proposed deletion of the Novice and Technician classes.[78] Other parties, including the QCWA and Barry Goldwater, urged the Commission to include all VHF privileges in the code-free class.

Accommodating these requests, the FCC adopted most of the original recommendations of the League's committee. As of 1991, a code-free Technician license granted privileges above 30 MHz, below which international law required a knowledge of the code. The holder could be upgraded to Technician Plus, with Novice HF privileges, upon passing a 5-wpm code test. The Novice license was retained as an alternate entry-level class and existing Technicians were grandfathered to Technician Plus. As the FCC's antiquated data processing equipment could not accommodate a sixth license class, "Plus" status was confirmed by a credit slip from the volunteer examiners, rather than on the license document, a situation finally remedied by the Commission's acquisition of new computers in 1994.[79]

Why did the amateur community support a code-free license after so many years of opposition? Traditions die hard, and hams shared a knowledge

of code for three-quarters of a century. Threats to amateur bands (such as 220 MHz) from other services emphasized the need for growth, and experience in other countries had demonstrated that a code-free license would attract many newcomers.

In addition, by the late 1980s, the microprocessor-controlled two-meter handy talky was firmly established as the major enticement to obtain a ham license. Code, to many, simply no longer appeared as a relevant requirement for this type of activity. The experience of the author, both on the air and as a volunteer examiner, is that the code-free license has been a powerful magnet to attract new amateurs and that fears of degraded amateur operations (ostensibly because code-free licensees have not demonstrated sufficient commitment to amateur radio) have largely proven overblown. Surely there are avenues other than by learning the code to make a commitment to amateur radio. Engaging in technical experimentation, public service events, nets and other on-the-air activities, and club meetings are just a few of the ways.

Have the written exams grown easier over the decades? While many amateurs think so, I do not. I took the Novice through Extra tests in the 1960s and 1970s and have ten years' experience as a volunteer examiner. I have studied an extensive collection of license manuals and, in addition, I have passed many other types of written tests, including the bar and CPA exams, and have given some as a college instructor. In my opinion, the difficulty level of the widely-held HF license exams has remained about the same, within the reach of motivated high school (and some younger) students. This is as it should be, for teenagers have always been the prime source of new radio amateurs. Study materials, on the other hand, have definitely improved over the past two decades. A newcomer who works through the ARRL's Technician ("Now You're Talking") and General Class license manuals will be a reasonably knowledgeable amateur.

I have also heard many hams complain that "open" question pools may simply be memorized. The old "question-and-answer" license manuals, however, also lent themselves to memorization. In my opinion, the new publicly-developed questions pools have resulted in better questions, more of them, and more up-to-date and comprehensive coverage of relevant rules and technology.

THE FUTURE

The amateur license structure of even a few years from now will surely differ from that of the present. Experimentation is an established part of amateur

radio, in its regulation as much as in its technical activities. A lesson of eight decades of adjustments is that the licensing system is never set in stone. Should code continue as a requirement for HF operation? Is the six-class structure too complex? Should license classes and requirements be internationalized? Are the written exams too difficult? Too easy?

Observing change is one of the joys of a lengthy amateur radio career (forming radio friendships is another). It is the changes in the new that make comparison with the old so interesting. Much of my on-air activity consists of arguing the merits of new equipment, new operating practices and, of course, new regulations. I anticipate with relish many heated discussions in the future.

ACKNOWLEDGEMENTS

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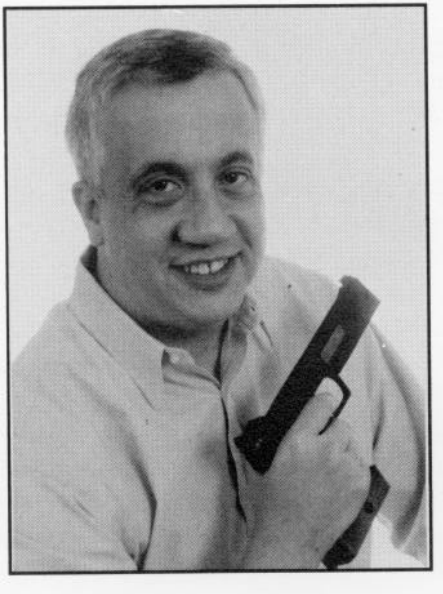
Neil is a lawyer and certified public accountant in Boulder, Colorado. While his wife (N0FNS) and children ski on winter weekends, he can be heard operating HF mobile from the summit of Vail Pass. An AWA member since the '70s, Neil wants to take this opportunity to thank all those whose efforts make the annual Rochester conference so enjoyable.



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